An Experimental Investigation on the External Condensation for a Vertical Tube under Forced Convection

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1. Introduction

Nowadays, the integrity of the nuclear power plant is suspected due to several nuclear accidents. As concerns about the safety of nuclear power plants have grown, the need for a passive safety system has also become a major issue. The passive containment cooling system (PCCS) is to remove the decay heat generated during an accident in the containment through condensation of circulating gas-steam mixture in the circumstance of the loss of power. Unlike the AP1000 which employs the steel containment vessel, a nuclear power plant with the concrete containment is supposed to introduce the condenser tubes inside the containment. Since the overall thermal performance of the PCCS is governed by the condensation heat transfer on the exterior surfaces of condenser tubes, it is necessary to study the condensation on the outer wall of the condenser tube.

Until now, studies on the outer wall steam condensation have been widely conducted by using theoretical and experimental ways under forced convection condition. Siddique [1] conducted to determine the effects of noncondensable gases on steam condensation under forced convection conditions. In this study, air-steam and helium-steam mixtures flowing downward inside a 46 mm internal diameter and 2.54 m long vertical tube was used. Also, Hasanein [2] carried out similar with the Siddique's experiment and represented with various nondimensional numbers such as Nu, Sc, etc. Kuhn [3] investigated experimentally local heat transfer inside a vertical tube and presented three different correlations for the evaluation of condensation heat transfer with the concept of degradation factor, diffusion layer theory and mass transfer theory. And Oh [4] carried out the experimental and theoretical investigation for a vertical in-tube condensation system and compared the results with Kuhn's experiment data. But unlike the condensation phenomenon in the vertical tube, the influence of the air-steam mixture on the outer wall condensation phenomenon has not been evaluated through controlled experiments. The objective of this study is to investigate experimentally characteristics of downward air-steam mixture flow on a vertical condenser tube under forced convection condition.

2. Experiments

2.1 Experiment apparatus

The schematic of the steam condensation test facility in Jeju National University (JNU) is shown in Fig. 1. The primary sections of the test facility include the steam generator, the test tank, and the condenser tube in the test tank. The inner diameter of chamber is 161.5 mm and the height is 1720 mm. A vertical tube with 40 mm in outer diameter, 5 mm in thickness and 1000 mm in length. Both of them are made of SUS-304. The steam is generated submerging heaters which is maximum 120 kW (30 kW × 4) in the steam generator and it mixed with air. The air-steam mixture moves to the chamber and condensed on the tube. The condensate flows to the condensate tank and it is sent to steam generator using the recirculation pump to maintain the water inventory.

Fig. 2. shows the location of thermocouples (K-type) in the tube. For measurement of the local heat flux, Each of 6 thermocouples (K-type) are inserted with two sets, inner wall surface and outer wall surface along the axial direction. In order to find distribution of gas mixtures in the chamber, 7 thermocouples arranged vertically along the tube height. The thermocouples on the tube wall are fixed with silver soldering shown in Fig. 3. For measuring the inner and outer wall surface temperature, the thermocouples were set with different depth.

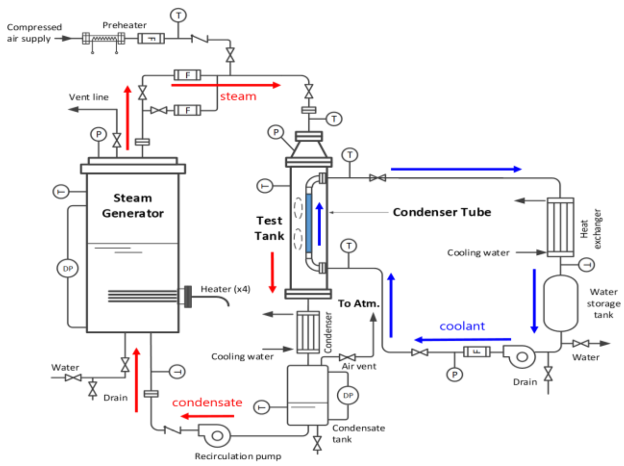


Fig. 1. Condensation experimental facility

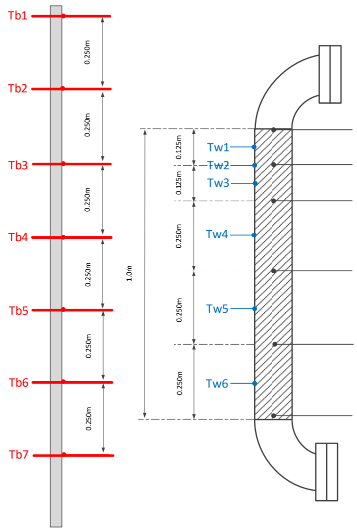


Fig. 2. Scheme of temperature measurement in test tank

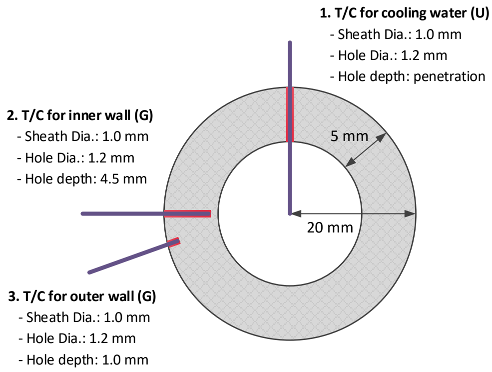


Fig. 3. Location of the inserted thermocouples in the cylinder

2.2 Data reduction

Since the location of the thermocouples was not installed at correct location due to the fabrication error, the measured values are corrected to the real surface temperatures as following [5]:

$$T_{wo} = T_{wo}^{*} - \frac{T_{wo}^{*} - T_{wi}^{*}}{\ln(r_i/r_o)} \ln(r_i^{*}/r_o), \quad (1)$$

$$T_{wi} = T_{wo} - \frac{T_{wo}^{*} - T_{wi}^{*}}{\ln(r_i^{*}/r_o^{*})} \ln(r_i/r_o), \quad (2)$$

where T_{wo}^{*} and T_{wi}^{*} denote the measured outer wall temperature and inner wall temperature, respectively; r_i^{*} and r_o^{*} represent inner and outer location of the installed thermocouples, respectively. The rate of condensation heat transfer is obtained from the heat removal rate by the coolant through the condenser tube in a steady state as:

$$q = \dot{m} c_p \left(T_{c,o} - T_{c,i}\right), \quad (3)$$

where $\dot{m}$, c_p, $T_{c,o}$, and $T_{c,i}$ are the mass flow rate of coolant, the specific heat, the outlet temperature, and inlet temperature of coolant, respectively. From the corrected surface temperatures, the local heat flux is calculated as follows:

$$q_i'' = k \frac{T_{wo,i} - T_{wi,i}}{r_o \ln(r_o/r_i)}. \quad (4)$$

where k, $T_{wi,i}$ and $T_{wo,i}$ represent conductive coefficient, the inner wall temperature, and outer wall temperature, respectively. The local heat transfer coefficient is obtained from calculated local heat flux by various measured temperature in a steady state as:

$$h_i = q''_i / (\mathrm{T}_{b,i} - \mathrm{T}_{w,i}) \quad (5)$$

$$\bar{h} = \frac{1}{L} \int h_x dx, \quad (6)$$

The results of the uncertainty analysis revealed that the average uncertainty of the heat transfer rate was 7.9%. Table 1 presents the condensation test matrix under forced convection condition.

Table I: Experiment matrix

Program	Pressure (bar)	Air mass fraction (%)	Wall subcooling (K)
Air-steam	2, 4	10 - 50	35 - 40

3. Result and discussion

3.1 Temperature distribution

Fig. 4. represents the distribution of temperature in the test tank. When the air-steam mixture flows downward in the test tank, difference of the bulk temperature is quite uniform within 3K. But wall temperature is changing according to the height. Since the steam in the mixed gas flows down the test section and condenses on the outer wall of the condenser, the amount of air is higher than the amount of steam in the lower part of the test tank. For this reason, the temperature of the wall surface at the lower end of the test tank is lower than the upper part.

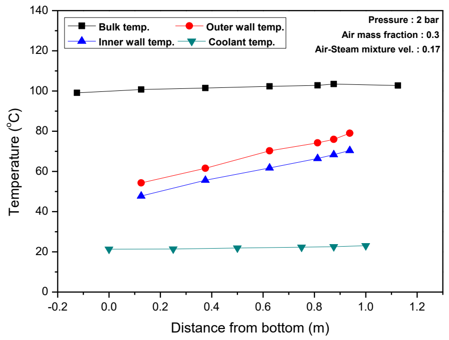


Fig. 4. Local temperature distribution according to height

Fig. 5. is the results of heat balance between the heat flux from the coolant and the wall. The average error is 7.9% and all the data are within error band of ±20 %. It means that the experiment is carried out with fairly high accuracy.

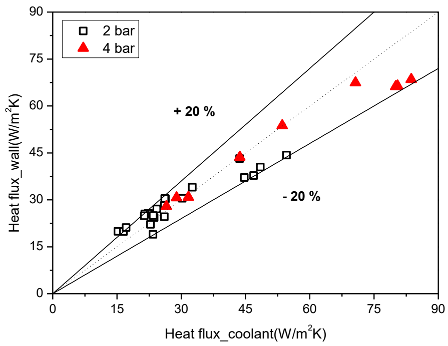


Fig. 5. Heat balance calculation @ 2 bar, 4 bar

Fig. 6. is plotted with air mass fraction. In the results, the heat transfer coefficient decreases with air mass fraction for a given pressure and velocity of mixture. As with the general trend, it can be confirmed that the heat transfer coefficient decreases when there is more air.

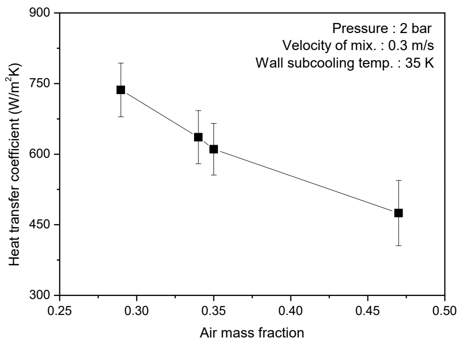


Fig. 6. Effect of the averaged air mass fraction

The distribution of heat transfer coefficient according to height is shown in Fig. 7. The heat transfer coefficient tends to gradually decrease with the direction of flow. And the heat transfer coefficient increases as the velocity of the mixture increases.

This graph shows the effect of the velocity of the mixture on the heat transfer coefficient. As the velocity of the mixture increases, the heat transfer coefficient increases. The reason is that as the mixture velocity increases, the flow of condensate on the wall of the condenser tube is influenced and the heat transfer coefficient increases due to the wavy effect. And It can be seen that the heat transfer coefficient decreases by about 60% on average at the four speeds as the mixture goes down to the bottom of the test tank.

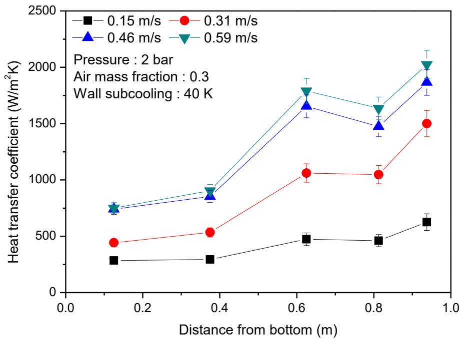
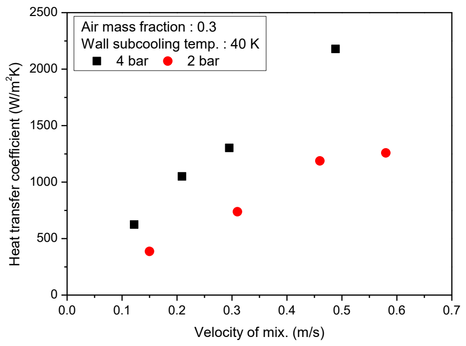
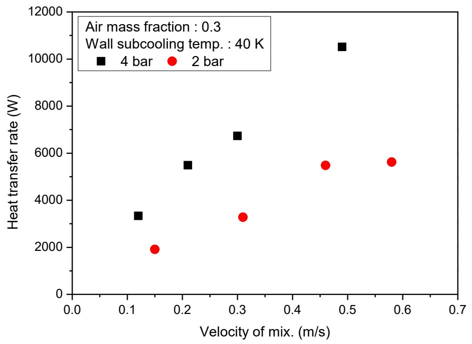


Fig. 7. Effect of the mixture velocity according to the height

Figs. 8. are showing the average value of the heat transfer coefficient and heat transfer rate according to the velocity of the mixture. Both of the results are having the similar tendency. Heat transfer coefficient and heat transfer rate increase as the velocity of mixture increases. As shown in the figure, the increase of the heat transfer coefficient according to the mixture velocity at 2 bar shows a tendency to converge after about 0.5 m / s, but it continues to increase at 4 bar. And also, the effect of pressure is represented at the averaged air mass fraction of 0.3. Heat transfer coefficient increases with the increase of pressure. The saturated steam density at each pressure increased with increasing pressure and thus it was confirmed that the heat transfer coefficient is higher in the similar wall subcooling and air mass fraction which is injected air-steam mixture.



(a)



(b)

Fig. 8. Comparison of effect of the mixture velocity between 2 and 4 bar condition (a) heat transfer coefficient (b) heat transfer rate

Previously, an experiment was conducted on a vertical condenser tube with 40 mm in outer diameter under natural convection condition in JNU [6]. Comparing the heat transfer coefficients between forced convection and natural convection, the results in natural convection are lower than those in forced convection in the Fig. 9. For air-steam velocity of 0.35 m/s, the heat transfer coefficient increased 1.3 times compared to the value at natural convection, and increased 2.3 times at 0.58 m/s.

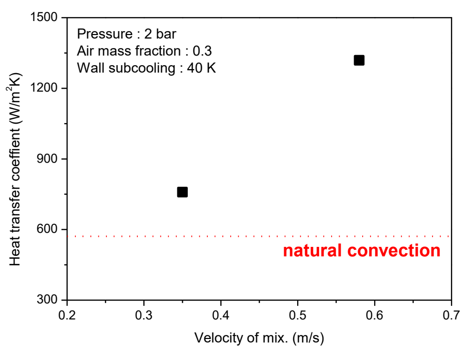


Fig. 9. Comparison of heat transfer coefficient between natural and forced convection

4. Conclusion

The condensation experiments were conducted under the forced convection condition for the vertical condenser tube with 40 mm in outer diameter. The investigation was carried out in the pressure range from 2 bar and 4 bar, and air mass fraction range from 0.10 to 0.50 conditions.

In this conducted experiment, heat transfer coefficient was obtained, mainly. Heat transfer coefficients in natural convection and forced convection conditions were compared. The influence of the air mass fraction, the velocity of the mixture, and the pressure.

For the Further work, additional experiments are going to be conducted with more various conditions for evaluation of effect of air-steam mixture.

ACKNOWLEDGEMENTS

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REFERENCES

[1] M. Siddique, The effects of noncondensable gases on steam condensation under forced convection conditions, Ph.D. Thesis, Massachusetts Institute of Technology, 1992.
[2] H. A. Hasanein, M. S. Kazimi and M. W. Golay, Forced convection in-tube steam condensation in the presence of noncondensable gases, International Journal of Heat and Mass Transfer, Vol.39, pp.2625-2639, 1996.
[3] S. Z. Kuhn, V. E. Schrock and P. F. Peterson, An investigation of condensation from steam-gas mixtures flowing downward inside a vertical tube, Nuclear Engineering and Design, Vol.177, pp.53-49, 1997.
[4] SeungMin Oh and Shripad T. Revankar, Experimental and theoretical investigation of film condensation with noncondensable gas, International Journal of Heat and Mass Transfer, Vol.49, pp.2523-2534, 2006.
[5] F. P. Incropera, D. P. Dewitt, T. L. Bergman, A. S. Lavine, Principles of Heat and Mass Transfer, Seventh edit International Student Version, p. 13, 2013.
[6] Y. G. Lee, Y. J. Jang and D. J. Choi, 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, Vol.104, pp. 1034-1047, 2017.