Development of a Correction Factor for Curvature Effect on Condensation Heat Transfer Coefficients on a Cylindrical Tubes

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1. Introduction

Fukushima nuclear accident and recent earthquakes in South Korea has drawn much attention to the integrity of the containment. With these concerns, an interest to the passive safety system has been increasing. The Passive Containment Cooling System (PCCS), that will be introduced in the next generation Korean nuclear power plant, guarantee the safety of the nuclear power by the condensation heat transfer phenomenon in the event of the loss of coolant accident (LOCA) or main steam line break (MSLB) to suppress the pressurization of the containment.

Various forms of empirical correlations for the heat transfer have been proposed. They include Uchida [1], Kawakubo [2], Dehbi [3], Liu [4], Jeon [5] and so on. These correlations reflect the effect on air mass fraction, pressure and temperature. However, they don't account for the enhancement of the condensation heat transfer coefficient by the tube curvature.

This study focused on developing the correction factor to consider the effect of the tube diameter on the condensation heat transfer coefficient based on the experimental data from a series of condensation tests. The heat transfer data were obtained from three condenser tubes with different outer diameter: 40 mm [6], 21.5 mm, and 10 mm [7]. The variation of the heat transfer coefficient according to the tube diameter was measured at the pressure ranging from 2 to 5 bar, and the air mass fraction from 0.1 to 0.8.

2. Experiment

2.1 Experiment Apparatus

Figure 1 depicts the experimental loop. The main sections of the experimental loop are the condensation section and the cooling section. The diameter of chamber is 609 mm and the height is 1950 mm. A vertical tube of 1000 mm in length installed inside of the chamber.

Figure 2 shows the location of the thermocouples (K-type) in the vertical tube. In order to measure the temperature on the tube, twelve thermocouples are embedded along the axial direction for measurement of inner and outer wall temperature. The thermocouples for inner and outer surface were located 4.5 mm and 1.0 mm deep from the base surface, respectively. Six thermocouples are installed to measure the coolant temperature.

Three condenser tubes with different outer diameter are fabricated. After a series of test runs are finished, the condenser tube in the test section is replaced by another one. The installation positions of the thermocouples are the same for three condenser tubes.

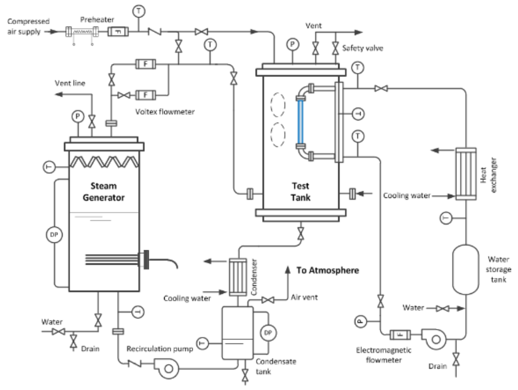


Fig. 1. Condensation experimental facility.

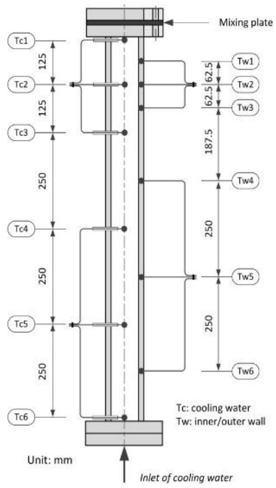


Fig. 2. Temperature measurement in the condenser tube.

2.2 Data Reduction

From the corrected surface temperatures, the local heat flux is calculated as follows [8]:

$$q'' = k\frac{T_{wo} - T_{wi}}{r_o \ln(r_o / r_i)}. \qquad (3)$$

where q'', k, T_{wo}, T_{wi}, r_o and r_i are the heat flux, the thermal conductivity, the temperature of outer wall, the temperature of inner wall, the radius of outer diameter, and the radius of inner diameter. 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:

$$q = \dot{m}c_p\left(T_{c,o} - T_{c,i}\right), \tag{4}$$

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. The condensation heat transfer coefficient is obtained by the fact that the rate of condensation heat transfer and convective heat removal by coolant are the same:

$$h = \frac{\dot{m}c_p(T_{c,o} - T_{c,i})}{A(T_{bulk} - T_{wall})}, \tag{5}$$

The results of the uncertainty analysis revealed that the average uncertainty of the heat transfer rate was 12.4%. Table 1 presents the three condensation tube test matrix under natural convection condition.

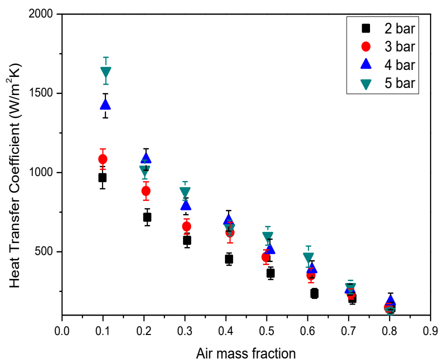
Table I: Test matrix

Gas composition	Pressure (bar)	Air mass fraction (%)	wall subcooling (K)
Air-steam	2 - 5	10 - 80	40

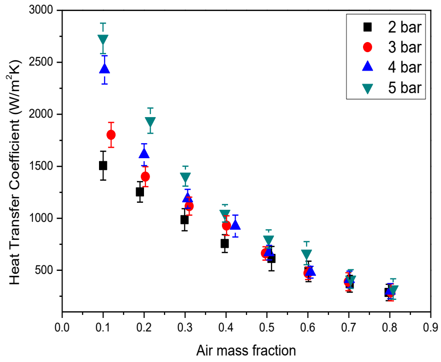
3. Result and discussion

3.1 Experiment Results

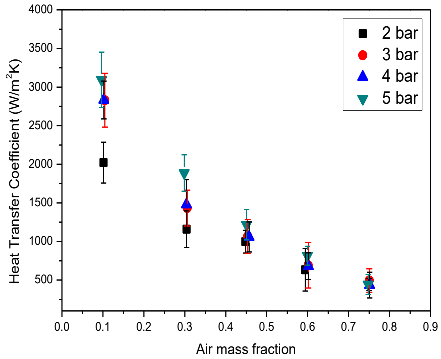
Figures 3 shows the heat transfer coefficient obtained for the three condenser tube at each pressure. The heat transfer coefficient decreases with an increase of the air mass fraction. In the presence of air, the air is accumulated near the liquid-vapor interface and inhibits heat transfer. These influences of a non-condensable gas are described in Collier [9].



(a) The heat transfer coefficient at 10-mm-O.D. tube



(b) The heat transfer coefficient at 21.5-mm-O.D. tube

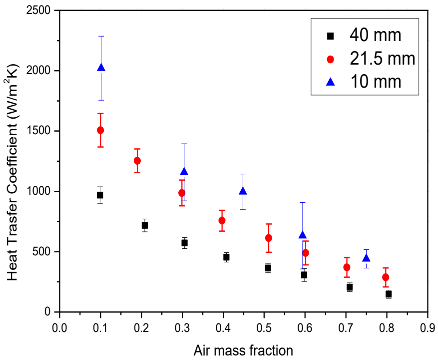


(c) The heat transfer coefficient at 40-mm-O.D. tube

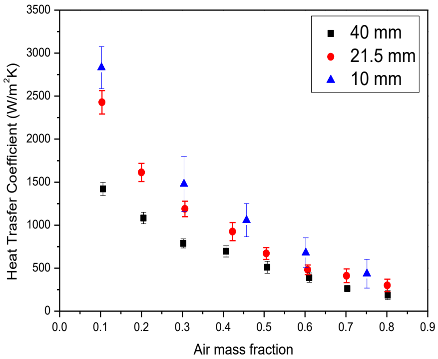
Fig. 3. The heat transfer coefficient by air mass fraction at each pressure

Figures 4 describe the comparison of total experimental results with different tube diameters. It was observed that the heat transfer coefficient increases as the diameter gets smaller under almost same condition. If the diameter decreases from 40 to 21.5 mm, the heat transfer coefficient is increased by 52% on average. And if the diameter decreases from 21.5 to 10 mm, the heat transfer coefficient is increased by approximately 39%.

It is observed that the heat transfer coefficient increases with an increase of the tube curvature. This experimental result demonstrates that, unlike all the previous empirical correlations which do not take into account the effect of the tube diameter, the condensation heat transfer coefficient is substantially influenced by this curvature effect. Thus, an improved correlation to account for the effects of not only the gas properties but the tube diameter is required for the best-estimated prediction of the heat removal rate by the PCCS.

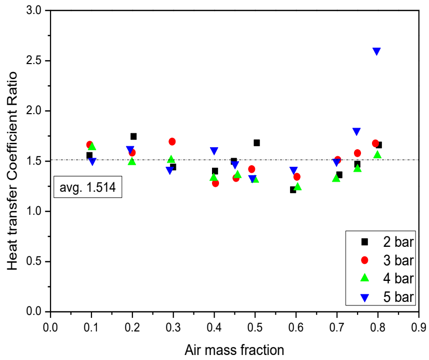


(a) Heat transfer coefficient at 2 bar

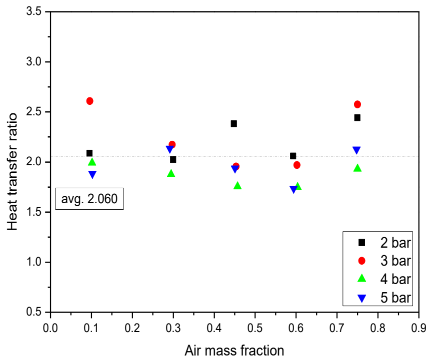


(b) Heat transfer coefficient at 4 bar

Fig. 4. The experimental data by air mass fraction at each diameter



(a) Heat transfer coefficient ratio by 21.5-mm-O.D. tube and 40-mm-O.D. tube



(b) Heat transfer coefficient by 10 mm and 40 mm

Fig. 5. The heat transfer coefficient ratio by diameter

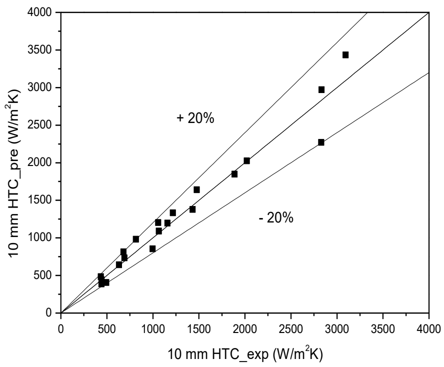
Figures 5 shows that the heat transfer coefficient ratio obtained from the comparison with test data of each condenser tube. Throughout the graph, the ratio of heat transfer coefficients changed little with the pressure or the air mass fraction. Based on the experimental results, a correction factor, f(D), for the tube diameter was developed so that it can be multiplied to a referenced empirical correlation by Lee et al. [6].

$$Nu_D = 890 Gr_L^{0.125} W_S^{*0.966} Ja^{-0.327} \cdot f(D) \qquad (7)$$

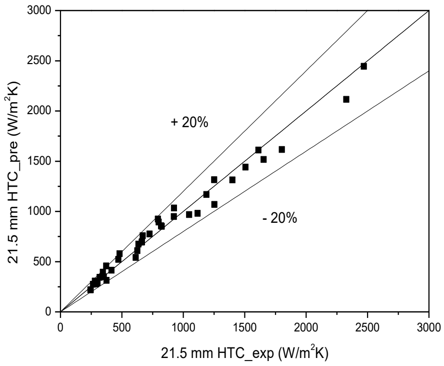
where $f(D)$ is based on 40–mm-O.D. tube data . The developed correction factor for curvature effect is expressed as:

$$f(D) = -0.788 \cdot \ln(D) - 1.536 , \qquad (8)$$

Figures 6 show the calculated result of heat transfer coefficients on the 10–mm-O.D. and 21.5–mm-O.D. tubes with this factor. The improved correlation (7) well predicts the change in heat transfer coefficient with varying diameters at various gas composition and gas pressure conditions. A tube with a diameter of 10 mm has an average error of 9.3% and a tube with a diameter of 21.5 mm has an average error of 9.0%.



(a) Error of calculated result using the correction factor at 10-mm-O.D. tube



(b) Error of calculated result using the correction factor at 21.5-mm-O.D. tube

Fig. 6. Error of calculated result using the correction factor

4. Conclusions

Three series of experiments were conducted to investigate the curvature effect of the rate of condensation heat transfer on a vertical condenser tube. The heat transfer coefficient was measured in the pressure range from 2 bar to 5 bar, and air mass fraction range from 0.1 to 0.8. The heat transfer coefficient increases with an increase of the tube curvature. A correlation factor needed for the empirical correlation was proposed based on experimental results. As a further work, through comparison with other experimental results, it is necessary to analyze the influence of the Gr number on the curvature effect and reflect it on the correction factor improvement.

ACKNOWLEDGEMENTS

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