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An Experimental Investigation of the Curvature Effect on Condensation Heat Transfer of the Air-steam Mixture on a Vertical Cylinder

Un-Ki Kim [a], Ji-Woong Yoo [a], Yeong-Jun Jang [a], Yeon-Gun Lee [a*]
[a] *Department of Nuclear and Energy Engineering, Jeju National University, # 66 Jejudaehakno, Jeju-si, Jeju, KOREA*
[*] *Corresponding author: yeongun2@jejunu.ac.kr*

1. Introduction

Recent earthquakes in South Korea has drawn much attention to the integrity of nuclear power. 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.

This study focused on the experimental investigation of the curvature effect about the rate the of condensation heat transfer on a vertical condenser tube under natural convection condition. The heat transfer data were obtained from three condenser tubes with different outer diameter: 40 mm [1], 21.5 mm, and 10 mm [2]. 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 condensation section includes chamber, condenser tube, steam generator, condensation water tank and recirculation pump. The cooling section has water storage tank and pump.

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. 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 steam is generated from submerging four heaters (Total 120 kW) in the steam generator and it goes to chamber. The steam is mixed with air in the chamber and condensed on the external surface of condenser tube. The condensate flows to the bottom of the chamber. And it is saved in condensate tank passed by the heat exchanger. The condensate is sent to steam generator utilizing the recirculation pump to maintain the water inventory.

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 find the coolant temperature.

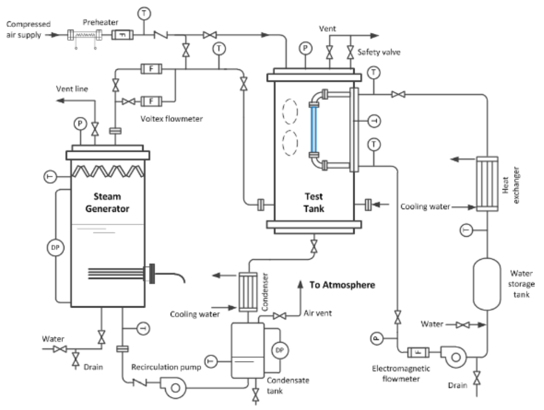


Fig. 1. Condensation experimental facility.

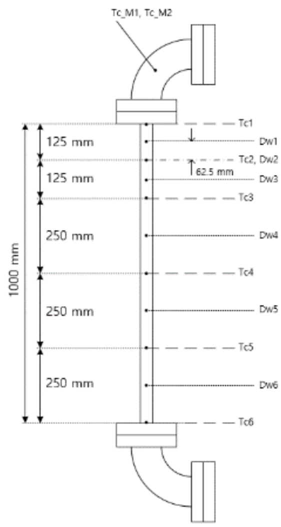


Fig. 2. Schematic diagram of temperature measurement.

2.2 Data Reduction

Since the location of the thermocouples was not installed at correct location due to the fabrication error, so installed depth was measures by depth gauge and the measured temperatures in this depth are corrected to the real surface temperatures as following [3]:

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

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

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. From the corrected surface temperatures, the local heat flux is calculated as follows:

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

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:

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

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:

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

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

Table I: Experiment matrix

Gas composition	Pressure (bar)	Air mass fraction (%)	Wall subcooling (K)
Air-steam	2 - 5	10 - 80	35 - 57

3. Result and discussion

3.1 Experiment Results

Figure 3 shows the heat transfer coefficient obtained for the condenser tube of 21.5 mm in outer diameter 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 [4].

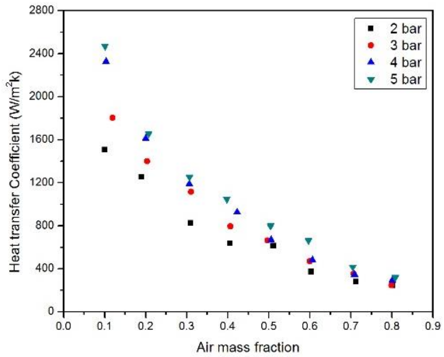
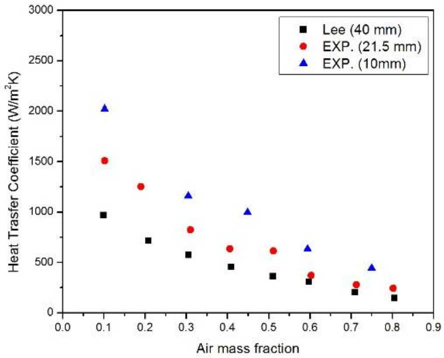
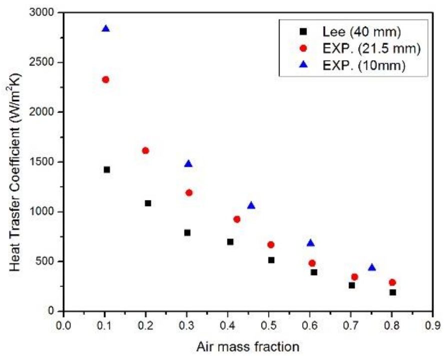


Fig. 3. The heat transfer coefficient by air mass fraction at each pressure

Figures 4 describe the comparison of total experiment 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%.



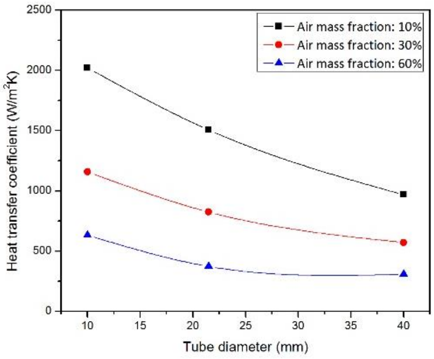
(a) Heat transfer coefficient at 2 bar



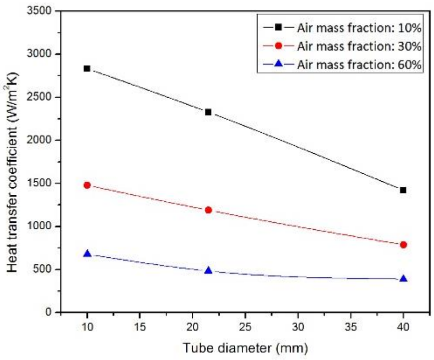
(b) Heat transfer coefficient at 4 bar

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

Figures 5 represent the variation of the heat transfer coefficient by the outer diameter of the condenser tube. It is clearly observed that the heat transfer coefficient increases with an increase of the tube curvature, and it changes in an exponential form. 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 advanced 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. Based on the experimental results, a correlating factor for the tube diameter will be developed in the future work so that it can be multiplied to a referenced empirical correlation by Lee et al. [1].



(a) Heat transfer coefficient by diameter at 2 bar



(b) Heat transfer coefficient by diameter at 4 bar

Fig. 5. The experimental data by diameter at each air mass fraction

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. It suggests that a correlating factor to account for the effect of the tube diameter is needed for the empirical correlation to predict accurately the heat transfer coefficient. As a further work, based on the obtained sets of experimental results, a comprehensive empirical correlation to consider the gas properties and the curvature effect will be developed

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