Experimental Investigation of the Tube Diameter Effect on the Condensation in the Steam-air Free Convection Condition

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1. Introduction

After the Fukushima accident, the integrity of the containment for the nuclear power plants has been emphasized in the station blackout accident. Passive containment cooling system (PCCS) is one of the promising passive safety features to reduce an increase of pressure inside the containment building under the postulated loss of coolant accident. In the accident, the heat exchangers of the PCCS condense the steam released from a reactor vessel without AC power. Recently, the Korean nuclear industry considers an adoption of tube bundle heat exchanger as PCCS heat exchanger. Some previous investigators conducted experimental studies on the condensation heat transfer in the steam-air mixture condition in order to evaluate the performance of heat removal of tube heat exchanger. They carried out condensation experiments mostly with a single tube in various steam-air mixture conditions and suggested correlations for prediction the condensation heat transfer coefficients as well. Dehbi [1] conducted single tube experiments using a copper tube with diameter 38 mm and length 3500 mm. Dehbi suggested a correlation for condensation on the flat plate even though experimental data was obtained from a single tube. Su et al. [2] performed condensation experiments with a stainless tube of which diameter and length are 38 mm and 2000 mm, respectively. They also suggested a correlation for the condensation in which the pressure of gas mixture, the air mass fraction and the wall subcooling are considered. Lee et al. [3] conducted experiments using a stainless tube with diameter 40 mm and length 1000 mm. Lee et al. developed a correlation consisting of dimensionless numbers obtained from non-dimensional governing equations for the condensation phenomena. Though many experiments were conducted with a single tube, investigation on the tube diameter for the condensation is limited.

In the present study, experiments were carried out by using three tubes with different diameters in order to observe the tube diameter effect.

2. Experimental Conditions

2.1 Experimental facility

The Fig. 1 shows an experimental apparatus for condensation with a single tube. The apparatus consists of pressurized vessel, condensation tube and coolant supply line. The pressurized vessel of which inner diameter is 1.0 m and height is 2.8 m. Steam is generated by 50 kW electric heater installed in the lower part of the pressurized vessel. The air supply line regulating the air mass fraction of the steam-air mixture is also connected to the side wall of the pressurized vessel.

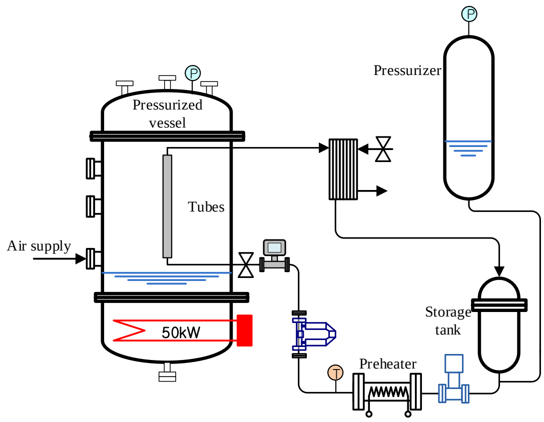

Fig. 1. Schematic diagram of experimental apparatus

The Fig. 2 shows a schematic diagram of condensing tube. The diameters of three condensing tubes are 21.5 mm, 33.6 mm and 42.4 mm. The detailed geometric conditions are described in the table I.

Temperatures of coolant flowing inside the tube are measured at five locations along the axial direction. The outer wall temperatures are measured at four points.

Table I: Geometric conditions of tube

Tube diameter (mm)	Tube length (mm)	Thickness (mm)
21.5	1328	5.0
33.6	1280	6.6
42.4	1280	6.5

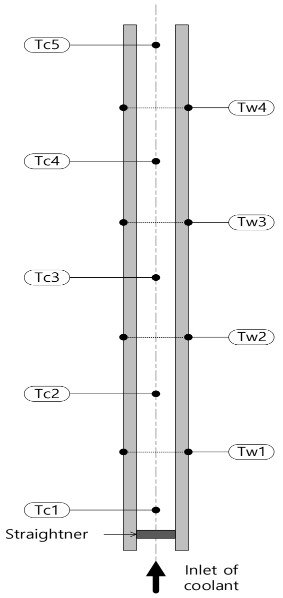

Fig. 2. Schematic diagram of condensation tube

2.2 Data reduction

The air mass fraction is the significant parameter affecting condensation phenomena in steam-air mixture. It is calculated based on the densities of steam and air, as follows,

$$W = \frac{\rho_{air}}{\rho_{air} + \rho_{steam}} \quad (1)$$

where W, ρ_{air}, ρ_{steam} are air mass fraction, air density and steam density, respectively.

The enthalpy energy change rate of coolant from inlet to outlet is used to estimate condensation heat transfer rate. It is calculated as follows,

$$\dot{Q} = \dot{m}\left(i(P,T_{c5}) - i(P,T_{c1})\right) \quad (2)$$

where $\dot{Q}$, $\dot{m}$, i are heat transfer rate, coolant mass flow and enthalpy energy, respectively. The enthalpy energy is obtained based on measured coolant temperature and pressure.

Finally, the heat transfer coefficient of condensation is obtained from the following equation.

$$h = \frac{\dot{Q}}{\pi d L(\overline{T_\infty} - \overline{T_w})} \quad (3)$$

where h, d, L, $\overline{T_\infty}$, $\overline{T_w}$ are heat transfer coefficient, tube diameter, tube length, bulk temperature of steam-air mixture and tube wall temperature, respectively.

2.3 Experimental conditions

Experimental conditions are prepared to investigate tube diameter effects as well as pressure, air mass fraction and wall subcooling. The table II shows the range of experimental parameters.

Table II: Experimental conditions

Pressure (bar)	2.0, 4.0, 5.0
Air mass fraction (-)	0.1, 0.2, 0.4, 0.7
Wall subcooling (K)	15 ~ 55

3. Experimental results

The Fig. 3 shows the heat transfer coefficients with respect to the air mass fraction and the tube diameter at the pressure of 4 bars and the wall subcooling of 40 K. As shown in the figure, the heat transfer coefficients decrease as the air mass fraction or the tube diameters increase.

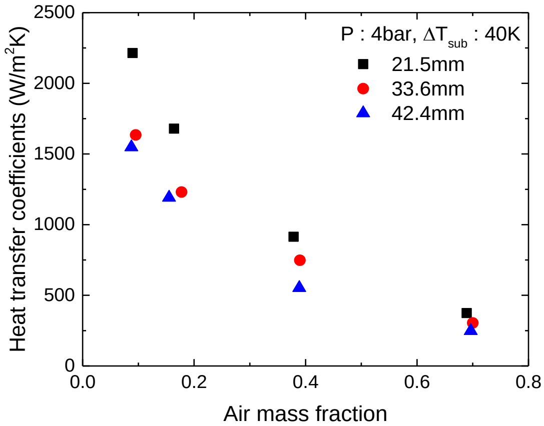

Fig. 3. Heat transfer coefficients according to air mass fraction and tube diameter

The Fig. 4 shows the comparison of heat transfer coefficients of the tube diameters 33.6 mm and 42.4 mm against that of 21.5 mm. The heat transfer coefficients for the 33.6 mm and 42.4 mm tube are respectively 25% and 31% lower than that of 21.5 mm tube at the given steam-air mixture conditions

The relation of the tube diameters effect in the present study is expressed as follows,

$$\frac{h_i}{h_{21.5}} \propto \left(\frac{d_i}{d_{21.5}}\right)^{-0.58} \quad (4)$$

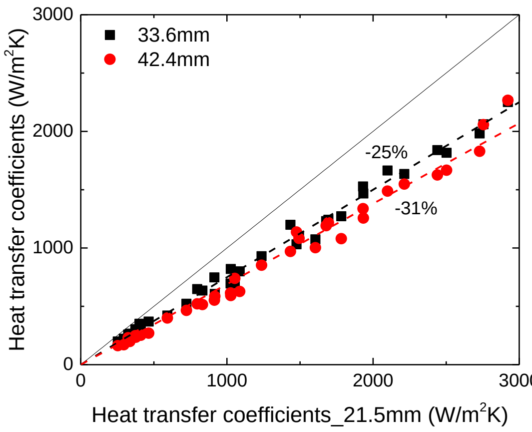

Fig. 4. Comparison of heat transfer coefficients of each tube

4. Analysis of curvature effect

The Eq. (4) was compared to Popiel [4] correlation which is accounting for the tube diameter effect on the free convection heat transfer. The correlation is used to account for the tube diameter effect in the condensation heat transfer model [5]. Popiel's model correlates the Nusselt numbers between the flat plate and the tube. It considers both the tube diameter and length as follows,

$$f = \frac{Nu_{tube}}{Nu_{plate}} = 1 + 0.3\left(\sqrt{32}Gr^{-1/4}\frac{l}{d}\right)^{0.909} \quad (5)$$

To compare the diameter effect of the Eq. (4) and Popiel correlation, the ratio of curvature effect of the Popiel's model was recast with that if 21.5 mm tube as follows,

$$\eta = \frac{f_d}{f_{21.5}} \quad (6)$$

where f_d is calculated by Popiel correlation at a given tube diameter.

As shown in the Fig. 5, there is a large discrepancy between Popiel's model and experimental data differently with the Eq. (4).

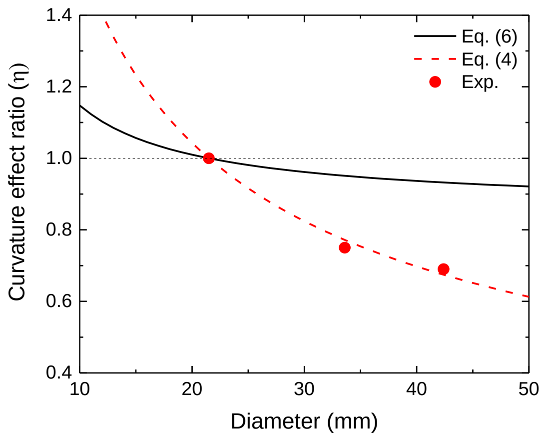

Fig. 5. Comparison of heat transfer coefficients of each tube

5. Conclusion

Experimental program was conducted to investigate the effect of tube diameter on the condensation heat transfer in the steam-air mixture condition. The experimental results showed that the condensation heat transfer coefficient decreases as tube diameter increases at a given steam-air mixture condition. The diameter effect is expressed by the power function with the reference tube diameter. It is found that the existing model for the tube diameter effect cannot predict well the present experimental data. Accordingly, it is necessary to develop a model that can predict the diameter effect under the condensation heat transfer condition.

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