Enhancement of the Condensation Heat Transfer Rate on a Vertical Tube with Annular Fins under Natural Convection Condition

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1. Introduction

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 to utilize the condensation heat transfer phenomenon. The condensation heat transfer phenomenon plays a key role in the event of the loss of coolant accident (LOCA) or main steam line break (MSLB) in suppressing the pressurization of the containment. Therefore, the heat removal rate of the PCCS is an important factor.

This experimental study investigates the condensation heat transfer on a vertical tube with annular fins for enhancement of condensation heat transfer under natural convection conditions. The geometry of the fin is determined by considering the pitch to diameter of the PCCS and to increase the heat transfer area against the bare tube's area. A bare tube's heat transfer data are utilized from a reference [1]. The finned tube experiments are conducted at the same conditions under which the bare tube experiments carried out.

2. Experiment

2.1 Experiment Apparatus

Figure 1 depicts the experimental loop. The experimental loop consists of the condensation section and the cooling section. The condensation section includes chamber which houses the condenser tube inside, 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 with 40 mm in outer diameter, 5 mm in thickness and 1000 mm in length is installed inside of the chamber. Both of them are made of SUS-304.

The steam is generated from submerging heaters (30 kW × 4) in the steam generator and it goes to chamber. The steam is mixed with air in the chamber and condensed on the tube. The condensate flows to the condensate tank and it is sent to the steam generator using the recirculation pump to maintain the water inventory.

Fig. 2 describes the location of thermocouples (K-type) in the tube and the chamber. To find internal gas mixtures distribution, 14 thermocouples with an azimu-thal interval of 90 degrees are installed inside of the chamber. For measurement of temperature on the tube, thermocouples are installed along the axial direction. This investigation is inspired by the experimental study of Liu [2]. The geometry of fin comes from the Liu's work. The design of the fin is determined by considering the pitch to diameter of the PCCS and total effective heat transfer area. The total effective heat transfer area of the finned tube is designed almost twice of that of the bare tube. Finally, the finned tube has the 13 fins of 80 mm in outer diameter and 5 mm in thickness.

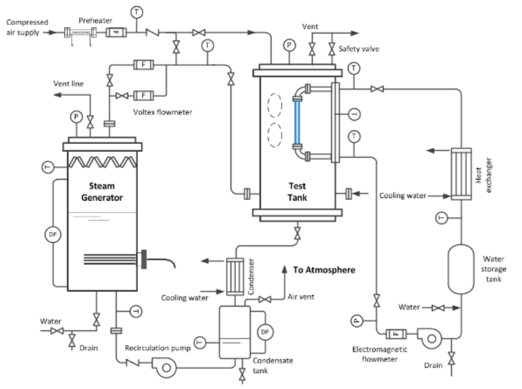


Fig. 1. Condensation experimental facility.

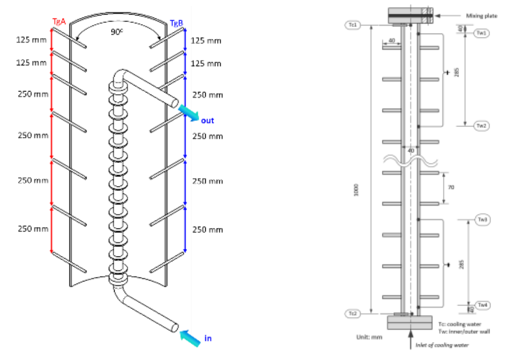


Fig. 2. Schematic diagram of temperature measurement.

2.2 Data Reduction

Since the sheath tips of thermocouples for wall temperatures were embedded inside the interior tube wall, the measured values are corrected to the real surface temperatures as following:

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

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

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

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

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:

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

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 results of the uncertainty analysis revealed that the maximum uncertainty of the heat transfer rate was 11.7%. Table 1 presents the condensation test matrix under natural convection condition.

Table I: Test matrix of the vertical tube with annular fins

Pressure (bar)	Air mass fraction (%)	Wall subcooling (K)	Coolant mass flow rate (kg/s)
2	30 ~ 70	34.2 ~ 36.4	0.13 ~ 0.25
3		32.7 ~ 40.8	0.12 ~ 0.26
4		38.2 ~ 40.3	0.12 ~ 0.35
5		33.4 ~ 41.5	0.11 ~ 0.31

3. Result and discussion

3.1 Experiment Results

Figure 3 is the photographs of the condensate liquid captured at 0.75 m from the top of the condenser tube at 4 bar. As shown in Fig. 3, the condensate was remained on the upper surfaces of the annular fin due to the surface tension. Once flooding occurred, some condensate scattered from the condenser tube to fall onto the test chamber floor and other condensate goes to the lower surface of the fin. These two kinds of condensate flows were caused by the surface tension.

Figure 4 describes the comparison results between the condensation heat transfer rate of the annular finned tube and that of the bare tube. From the experimental results, the overall trends followed those generally reported for condensation heat transfer; the rate of heat transfer increases with increasing the pressure and decreases with increasing the air mass fraction. The heat transfer rate increased with an increase in pressure due to the effect of ascent of the steam density. The noncondensable gas, air, accumula-ted near the liquid film. This accumulated layer plays an obstacle during the condensation phenomenon, as physically explained by Collier and Thome [3]. For a quantitative comparison, the enhancement factor (EF) for the finned tube was defined as:

$$EF = \frac{h_f A_f}{h_b A_b}, \quad (5)$$

where h_f, h_b, A_f, and A_b represent heat transfer coefficients of the finned tube and the bare tube, and the total surface area of both tubes, respectively.

The enhancement factor distributed between 1.25 and 1.88. It did not show any tendency on the pressure or the air mass fraction. The average enhancement factor was 1.54, which lower than the ratio of the effective heat transfer, 1.84. This result from two reasons; the disturbance of the natural circulation flow and the presence of the condensate on the upper surface of the fin.

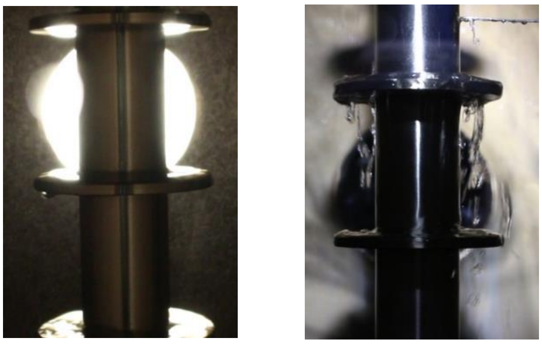


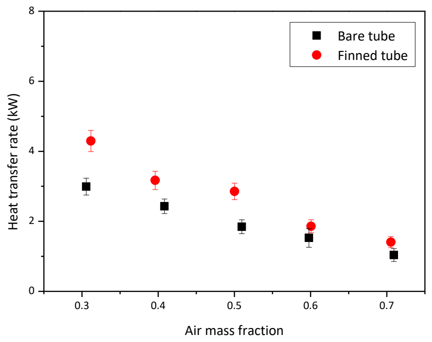
Fig. 3. Photos of the condensate on annular fins.

3.2 Applicability to PCCS bundle

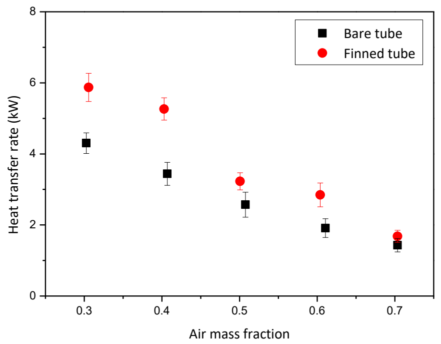
The main purpose of this work was an experimental demonstration of the enhancement of the heat removal rate for the PCCS to guarantee the safety of the containment building. With regard to the shape of fins, Tong et al. [4] carried out very similar experiment by using the longitudinal finned tube. According to Tong's experimental results, the heat transfer rate of the finned tube was not enhanced before the air mass fraction reached 75 %. From the results, the longitudinal fins do not always assure the enhancement of heat transfer.

In these point of view, the vertical tube with annular fins could be a better possible option to apply to the PCCS. However, it also has the pros and cons in the condensation heat transfer. That's why the optimization of geometry of fin must be carried out for the maximum heat capacity for the PCCS. The main parameters of design of the fin include height of fin, thickness, fin spacing and tilting angle for the drainage of condensate. This remains as a future work.

Another key consideration is the configuration of PCCS. The PCCS consists of lots of condenser tubes. Those condensers lead to degrades the enhancement of heat transfer due to the bundle effect. The presence of the fins in the tube bundles causes difficulties in fabrication and repair for the maintenance. Moreover, these fins disturbance the condensation physical phenomena, such as steam diffusion for the longitudinal fins and natural circulation for the annular fins.



(a) Heat transfer rates at 2 bar



(b) Heat transfer rates at 4 bar

Fig. 4. Comparison of the heat transfer rates between the finned tube and the bare tube.

4. Conclusions

The condensation heat transfer experiments were conducted utilizing the vertical condenser tube with annular fins of 40 mm in outer diameter of tube, 80 mm in outer diameter of fin and 1000 mm in length in the presence of the air under natural convection conditions. The total rate of heat transfer was measured in the pressure range between 2 and 5 bar, and the air mass fraction from 0.3 to 0.7. The experimental results compared with results of the bare tube.

In the visualization results, the annular fins hold the condensate until it floods due to the surface tension. The condensate on the upper surface of annular fins disturb the heat transfer phenomena, as expected.

The heat transfer rate of finned tube is enhanced enough comparison with that of bare tube. However, the heat flux of finned tube is decreased comparison with that of bare tube. This is caused by the disturbance of the axial flow by the annular fin and the existence of the condensate film on the upper surface of the fin. Nevertheless, it is experimental results demonstrated clearly the enhancement of heat transfer rate by using the annular fins. Thus, the annular fin will be a more plausible option than the longitudinal fin for the PCCS.

This investigation will be helpful to determine the fundamental geometry of finned tube for the PCCS.

ACKNOWLEDGEMENTS

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