*Transactions of the Korean Nuclear Society Spring Meeting*
*Jeju, Korea, May 7-8, 2015*

# Subcooled Pool Boiling from Two Tubes of 6 Degree Included Angle in Vertical Alignment

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## 1. Introduction

One of the major issues in the design of a heat exchanger is the heat transfer in a tube bundle. The passive condensation heat exchanger (PCHX) adopted in APR+ has U-type tube [1]. The PCHX is submerged in the passive condensation cooling tank (PCCT). The heat exchanging tubes are in vertical alignment and inclined at 3 degrees to prevent water hammer as shown in Fig. 1. For the cases, the upper tube is affected by the lower tube. Therefore, the results for a single tube are not applicable to the design of the PCHX.

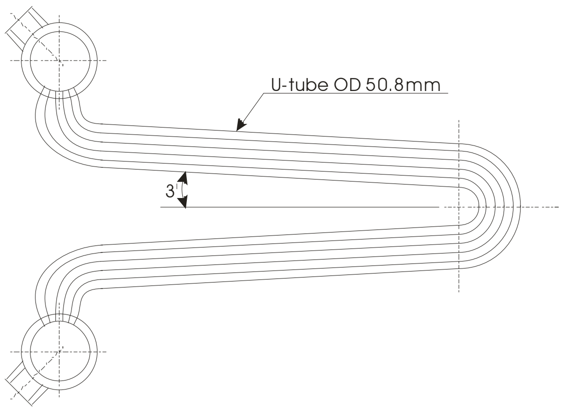


Fig. 1. Schematic view of PCHX in APR+ passive auxiliary feedwater system (PAFS).

However, the passive heat exchangers are submerged in the subcooled water under atmospheric pressure. The water temperature in the PCCT rises according to the PAFS actuation and reaches the saturation temperature after more than 2.5 hours [1]. Since this period is very important to maintain reactor integrity, the exact evaluation of heat transfer on the tube bundle is indispensable. Although an experimental study on both subcooled and saturated pool boiling of water was performed to obtain local heat transfer coefficients on a 3 degree inclined tube at atmospheric pressure by Kang [2], no previous results were treating the bundle effect in the subcooled liquid.

The heat transfer on the upper tube is enhanced compared with the single tube. The enhancement of the heat transfer on the upper tube is estimated by the bundle effect ( $h_r$ ). It is defined as the ratio of the heat transfer coefficient ( $h_b$ ) for an upper tube in a bundle with lower tubes activated to that for the same tube activated alone in the bundle [3]. The upper tube within a tube bundle can significantly increase nucleated boiling heat transfer compared to the lower tubes at moderate heat fluxes. Since the source of the convective flow in pool boiling is the lower heated tube, the heat flux of the lower tube ( $q''_L$ ) is of interest. Recently, Kang [4] carried out an experimental parametric study of tandem tubes under pool boiling conditions to determine the effects of the tube pitch, elevation angle, and the heat flux of the lower tube on pool boiling heat transfer.

Summarizing the published results, it is still necessary to identify effects of liquid subcooling on inclined tubes for application to the PCHX design. Therefore, the present study is aimed to study the variations of pool boiling heat transfer on a tube bundle having a 6 degree included angle in vertical alignment and submerged in subcooled water at atmospheric pressure.

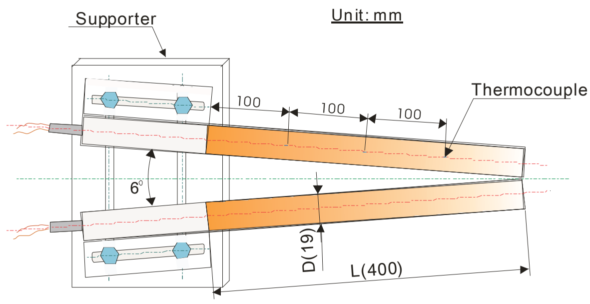


Fig. 2. Assembled test section.

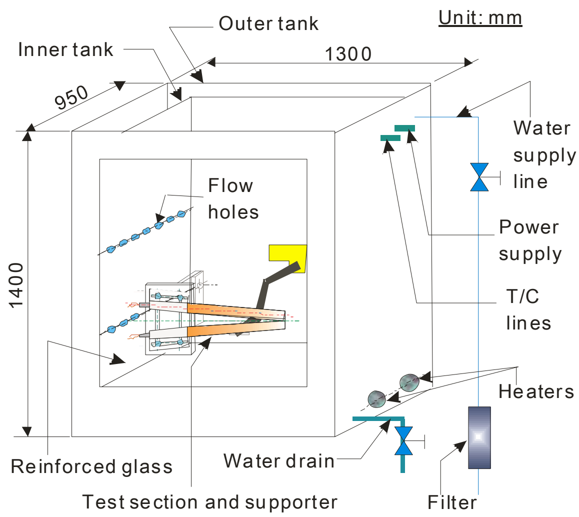


Fig. 3. Schematic of experimental apparatus.

## 2. Experiments

For the tests, the assembled test section (Fig. 2) was located in a water tank which had a rectangular cross section (950×1300 mm) and a height of 1400 mm as shown in Fig. 3. The heat exchanging tube is a resistance heater made of a very smooth stainless steel tube of 19 mm outside diameter ( $D$ ) and 400 mm heated length ( $L$ ). The tube was finished through a buffing process to have a smooth surface (roughness: $R_a$ =0.15μm).

The included angle was set as 6°. The heat flux of the lower tube was set a fixed value of 0, 30, 60, and 90 kW/m$^2$. The water tank was filled with the filtered tap water until the initial water level reached 1.1 m; the water was then heated using four pre-heaters at constant power. When the water temperature was reached at a proper value, the power supply to the test section was activated. The heat flux on the test section ( $q''_T$ ) was fixed (i.e., 30, 60, 90, and 120 kW/m$^2$) and heating of the water was started until it got saturated. The temperatures of the tube surfaces ( $T_W$ ) and the water ( $T_{wat}$ ) were measured through the heating process. Once a test for a set of $q''_L$ and $q''_T$ was completed the liquid was cooled down lower than 50 °C. Then another set of heat fluxes was tested.

The tube outside was instrumented with six T-type sheathed thermocouples (diameter is 1.5 mm). The thermocouple tip (about 10 mm) was brazed on the sides of the tube wall. The water temperatures were measured with six sheathed T-type thermocouples attached to a stainless steel tube that placed vertically in a corner of the inside tank. All thermocouples were calibrated at a saturation value (100 °C since all tests are done at atmospheric pressure). To measure and/or control the supplied voltage and current, two power supply systems were used.

The heat flux from the electrically heated tube surface is calculated from the measured values of the input power as follows:

$$q''_T = \frac{VI}{\pi DL} = h_b \Delta T = h_b (T_W - T_{wat}) \tag{1}$$

where $V$ and $I$ are the supplied voltage and current, and $D$ and $L$ are the outside diameter and the length of the heated tube, respectively. $T_W$ and $T_{wat}$ represent the measured temperatures of the tube surface and the water, respectively. Every temperature used in Eq. (1) is the arithmetic average value of the temperatures measured by the thermocouples.

The uncertainties of the experimental data were calculated from the law of error propagation [5]. The 95 percent confidence uncertainty of the measured temperature has the value of ±0.11 °C. The uncertainty in the heat flux was estimated to be ±0.7%. Since the values of the heat transfer coefficient were the results of the calculation of $q''_T / \Delta T$ , a statistical analysis of the results was performed. After calculating and taking the mean of the uncertainties of the propagation errors, the uncertainty of the heat transfer coefficient was determined to be ±6%.

## 3. Results

Figure 3 shows plots of $\Delta T_{sat}$ versus $\Delta T_{sub}$ data for $q''_T$ =30kW/m$^2$. The wall superheat ( $\Delta T_{sat} = T_W - T_{sat}$ ) increases for a while and, then, decreases as the degree of liquid subcooling ( $\Delta T_{sub} = T_{sat} - T_{wat}$ ) increases. The value of $\Delta T_{sat}$ is increasing gradually until $\Delta T_{sub}$ reaches at 7 °C at $q''_L$ =0 kW/m². Then, $\Delta T_{sat}$ decreases as $\Delta T_{sub}$ increases. The increase of $q''_L$ results in the decrease of $\Delta T_{sat}$ at fixed $\Delta T_{sub}$ .

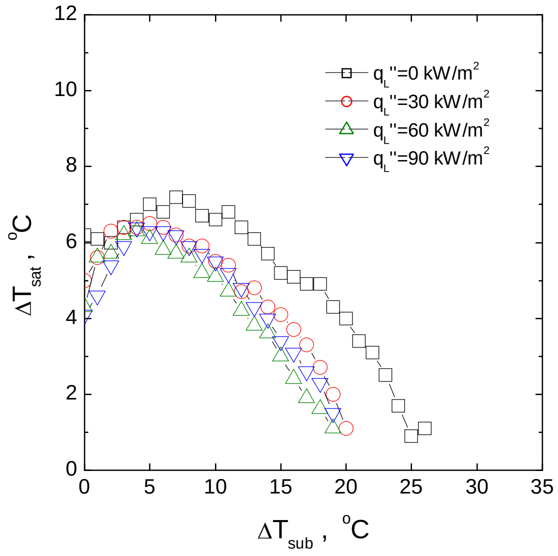


Fig. 4. Plots of $\Delta T_{sat}$ against $\Delta T_{sub}$ at $q''_T$ =30kW/m$^2$.

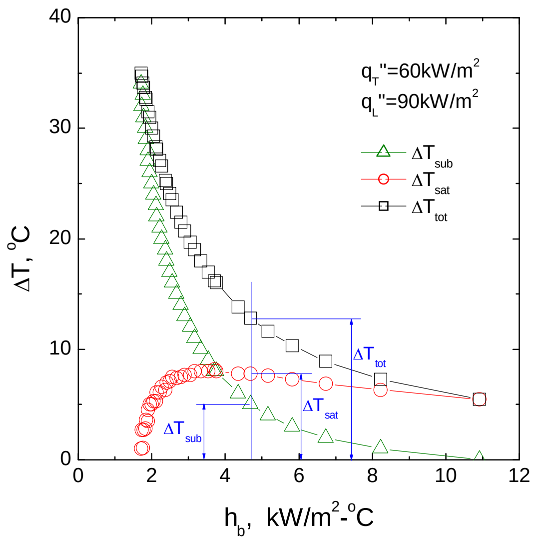


Fig. 5. Relation between $h_b$ and $\Delta T$ .

The $\Delta T$ shown in Eq. (1) can be rewritten as $\Delta T_{sat} + \Delta T_{sub}$. That is, $h_b = q''/(\Delta T_{sat} + \Delta T_{sub})$. The values of $\Delta T_{sat}$ and $\Delta T_{sub}$ represent the conditions of the tube surface and the water, respectively. The increase in $\Delta T_{sat}$ enhances the generation of bubbles whereas the increase in $\Delta T_{sub}$ suppresses the generation of bubbles. As the liquid becomes saturated $h_b$ increases suddenly and, then, the value of $\Delta T_{sat} + \Delta T_{sub}$ decreases accordingly. The relation between the differences in temperatures and the heat transfer coefficient is shown in Fig. 5. $\Delta T_{sat}$ shows a sudden increase and, then, slightly decreases as $h_b$ increases.

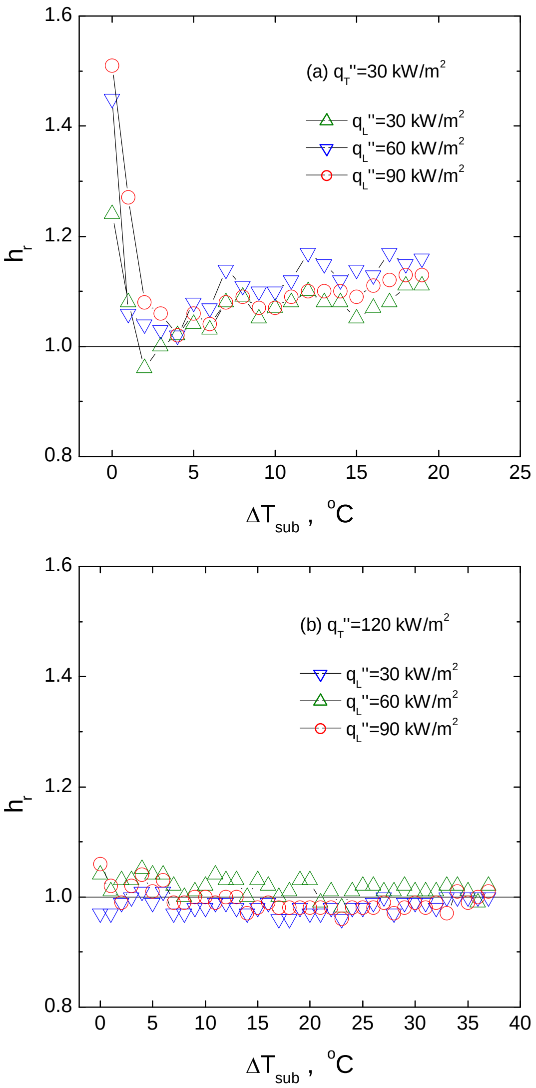


Fig. 6. Plots of $h_r$ against $\Delta T_{sub}$.

The variation of bundle effect against $\Delta T_{sub}$ is shown in Fig. 6. The heat transfer on the upper tube is enhanced compared with the single tube. The bundle effect is clearly observed at $q_T''$ =30kW/m$^2$ and $q_L''$ =90kW/m$^2$. The bundle effect is expected as the convective inflow of bubbles and liquid, rising from the lower tube, enhances the heat transfer on the upper tube [4]. The intensity of the convective flow is increased as $q_L''$ increases. The heat transfer on the upper tube is associated with (1) the bulk movement of bubbles and liquid coming from the lower side and (2) the bubble nucleation and growth on the tube surface. The possible mechanisms affecting on heat transfer are convective flow, liquid agitation, and the nucleation site density. The increase in the heat flux also increases the nucleation sites which enhancing heat transfer. The convective flow generated by the bulk movement increases heat transfer and is important for the heat transfer analysis at low heat fluxes. The liquid agitation also enhances heat transfer. The intensity of the liquid agitation depends on the amount of bubbles and the active movement of the bubbles. When the upper tube is at low heat flux a convection-controlled regime prevails. Therefore, the turbulent flow generated by the departed bubbles from the lower tube enhances heat transfer much. However, as the heat flux of the upper tube increases, the portion of the liquid convection is decreased and, accordingly, the enhancement in heat transfer is decreased. The increase of $\Delta T_{sub}$ decreases $h_r$. As the subcooling increases the sizes of the bubbles are decreased. Therefore, the convective flow generated by the lower tube becomes weaker. This results in the decrease of $h_r$.

## 4. Conclusions

An experimental study was performed to investigate the combined effects of $\Delta T_{sub}$ and $q_L''$ on pool boiling heat transfer on the upper tube of a tube bundle having 6 degree included angle. The bundle effect is decreased as the liquid subcooling increases whereas it is increased as the heat flux of the lower tube increases. The increase in the bundle effect is clearly observed as the heat flux of the upper tube is low. This tendency is related with the convective flow and the sizes of the generated bubbles.

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