Effects of Included Angle on Pool Boiling Heat Transfer of Tube Array Having Horizontal Lower Tube

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1. Introduction

One of the major issues in the design of the advanced nuclear reactor is the adoption of passive systems that maintain safety functions in case of no power supply [1,2]. The time to sustain the integrity of a reactor is highly dependent on the heat removal capacity of the systems. Since the decay heat of a reactor is removed through passive type heat exchangers, to identify the exact heat transfer rate to the pool side is the most important design factor.

In the design of a heat exchanger, the arrangement of tubes is very important. The upper tube is affected by the lower 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]. Since heat transfer is related to the conditions of a tube surface, bundle geometries, and a liquid type, lots of studies have been carried out for the combinations of those parameters [4,5].

Many researchers have investigated effects of a tube pitch on heat transfer enhancement [6-10]. The heat transfer of the upper tube within a tube bundle is significantly increased compared to the lower tubes at moderate heat fluxes. At high heat fluxes, this influence disappears and the data merge onto the pool boiling curve of a single tube [11]. It was explained that the major influential factor is the convective effects due to the fluid velocity and the rising bubbles [5].

Since the source of the convective flow in pool boiling is the lower heated tube, the heat transfer change due to the heat flux of the lower tube, q''_L , is of interest. Ustinov et al. [12] investigated effects of the heat flux of lower tube on pool boiling of the upper tube for the fixed tube pitch. They used microstructure-R134a or FC-3184 combinations and identified that the increase in the heat flux of the lower tube decreased the superheat (ΔT_{sat}) of the upper tube.

A similar design parameter compared to the tube pitch is an included angle (δ) between tubes. The passive condensers adopted in SWR1000 and APR+ have U-type tubes [1,2] in vertical alignment. For the cases, the heat transfer is highly dependent on the included angle. Recently, Kang [13] studied the included angle between two tubes inclined as $\pm\delta/2$ from the horizontal and identified that the increase of the angle increased the bundle effect. This kind of vertical symmetry tubes is found in APR+. If the inclinations of the tubes are not vertical symmetry, the heat transfer can be changed. Therefore, the present study is aimed to identify the effects of the included angle while the inclination angles of the tubes are vertically asymmetry. The effect of the heat flux of the lower tube on heat transfer of the upper tube is also investigated. To the present author's knowledge, no results on this effect have as yet been published.

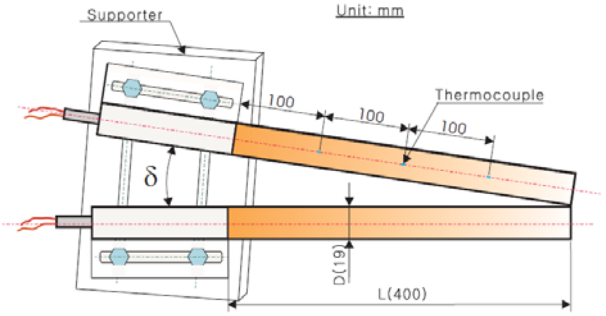

Fig. 1. Schematic diagram of test section.

Table 1. Test Matrix

δ , deg	q''_L , kW/m²	q''_T , kW/m²
2	0, 60, q''_T	10-120
6	0, 60, q''_T	10-120
10	0, 60, q''_T	10-120
14	0, 60, q''_T	10-120
18	0, 60, q''_T	10-120
24	0, 60, q''_T	10-120

2. Experiments

For the tests, the assembled test section (Fig. 1) was located in a water tank which had a rectangular cross section (950×1300 mm) and a height of 1400 mm. The heat exchanging tubes are resistance heaters made of a very smooth stainless steel tube of 19 mm diameter (D). The included angle was regulated by adjusting the upper tube. The lower tube is situated horizontally. The angle (shown in Fig. 1) between the tubes was varied from 2° to 24°. The test matrix for the investigation is shown in Table 1. q''_T is the heat flux of the upper tube surface.

The tube outside was instrumented with six T-type sheathed thermocouples. The thermocouples were brazed on the sides of the tube. The local heat transfer coefficient measured at the sides can be recommended as the average value of the tube periphery [14].The water temperatures were measured with six sheathed T-type thermocouples that placed vertically at a corner of the inside tank. All thermocouples were calibrated at a saturation value (100 °C since all tests were done at atmospheric pressure). To measure and/or control the supplied voltage and current, power supply systems were used.

After the water tank was filled with 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 the saturation value, the water was then boiled for 30 minutes to remove the dissolved air. The temperatures of the tube surfaces were measured when they were at steady state while controlling the heat flux on the upper tube surface with input power.

The uncertainties of the experimental data were calculated from the law of error propagation [15]. The uncertainty of the measured temperature had 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 $q''_T / \Delta T_{sat}$, a statistical analysis on 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 2 shows plots of q''_T versus ΔT_{sat} data obtained from the experiments. The q''_L was changed for δ =6°. As shown in the figure the heat transfer on the upper tube of the tube array is enhanced compared with the single tube (i.e., q''_L =0kW/m^2). The change of q''_L from 60 to 0kW/m^2 results in 50% (from 4.8 to 7.2°C) increase of ΔT_{sat} when q''_T =30kW/m^2. The increase of q''_L results in the decrease of ΔT_{sat} for the given heat flux. Throughout the heat fluxes tested the enhancement in heat transfer is much clearly observed at low or moderate heat fluxes. When q''_T >100kW/m^2 the curve for $q''_L \neq$ 0kW/m^2 converges to the curve for the single tube.

Figure 3 shows variations in the bundle effect against the heat flux of the upper tube for δ =24°. As the heat flux of the upper tube increases from 10 to 120kW/m^2, the bundle effect decreases dramatically from 3.26 to 1.09 for q''_L =60 kW/m^2. The maximum bundle effect is observed at the lowest heat flux (i.e., q''_T =10 kW/m^2). Significant bundle effect is observed as q''_T is less than 60kW/m^2. However, the bundle effect converges to unity at higher heat fluxes greater than 100kW/m^2, regardless of the heat flux of the lower tube. Throughout the heat fluxes tested, the increase of q''_L enhances the bundle effect.

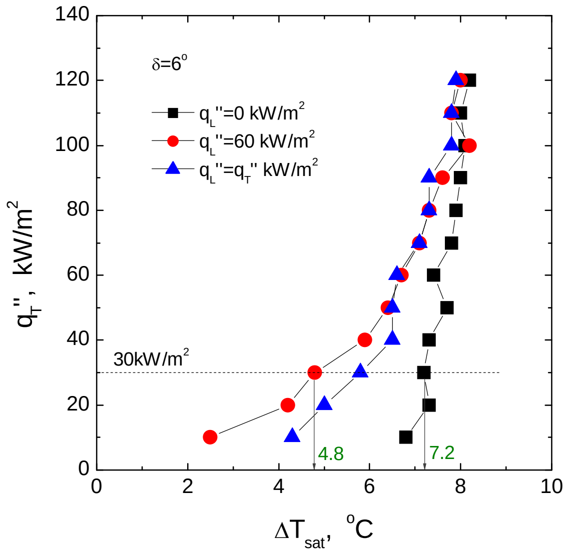

Fig. 2. Plots of q''_T versus ΔT_{sat}.

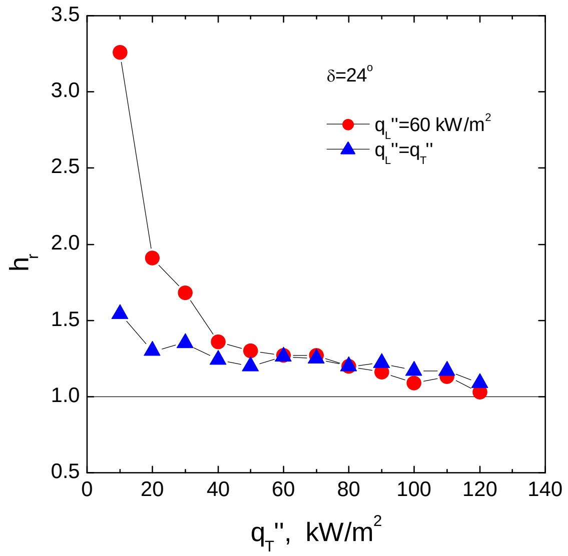

Fig. 3. Variations in bundle effect for δ =24°.

The bundle effect is expected as the convective flow of bubbles and liquid, rising from the lower tube, enhances the heat transfer on the upper tube [10]. 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 bubble and liquid coming from the lower side and (2) micro-convective component relates to the heat transfer associated with the bubble nucleation and growth on the tube surface [9]. 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 gets decreased and the enhancement in heat transfer gets decreased.

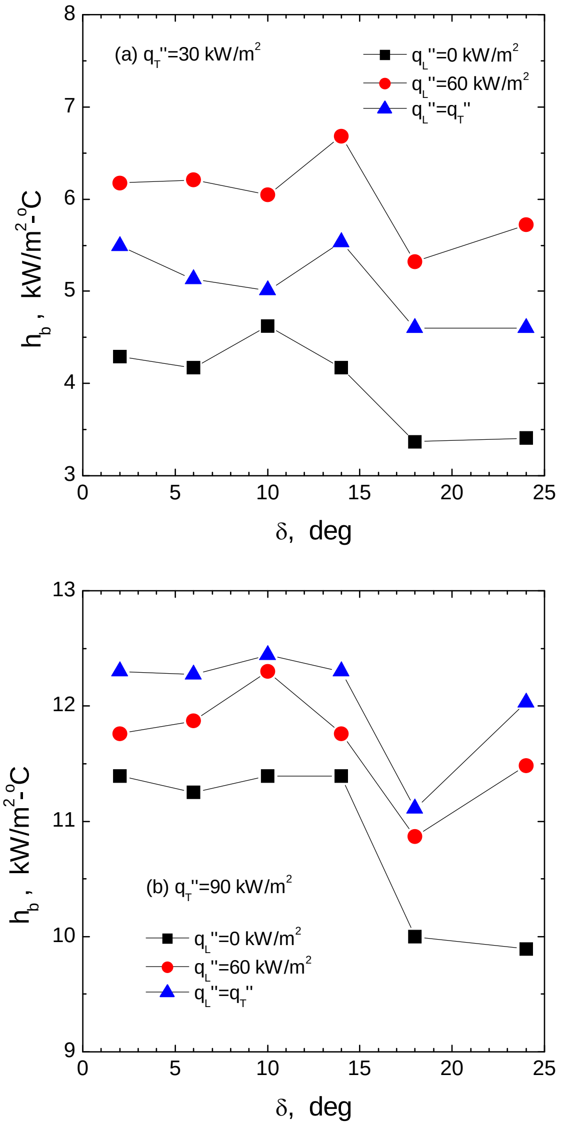

Fig. 4. Plots of h_b versus δ at q_T'' =30 and 90kW/m^2.

To identify the effects of the included angle the heat transfer coefficients were obtained for the different q_L'' as the included angle changes from 2° to 24°. Results for q_T'' =30 and 90kW/m^2 are shown in Fig. 4. There are no significant changes in h_b as δ <14°. However, the increase of δ eventually decreases the heat transfer coefficient of the upper tube. When $q_L'' \neq$ 0kW/m^2, slight increase in h_b is observed at δ =24°. Through the included angles, two competing heat transfer mechanisms can be considered. One of them is the dispersion of the convective flow and the other one is the effects of turbulence [15]. The upward flow of liquid and bubbles disperses moving along the height and affects the heat transfer of the upper tube. The intensity of the flow is dependent on the heat flux of the lower tube and the location of the tubes. The dispersion of the upward flow is increased as the included angle increases. This reduces the intensity of the convective flow and eventually decreases the heat transfer coefficient of the upper tube. Since the mixture of the liquid and bubbles coming from the lower tube needs some distance to generate enough turbulent effect [16], a slight increase in heat transfer is observed at δ =24°. The tendency is clearly observed as the heat flux of the lower tube is high.

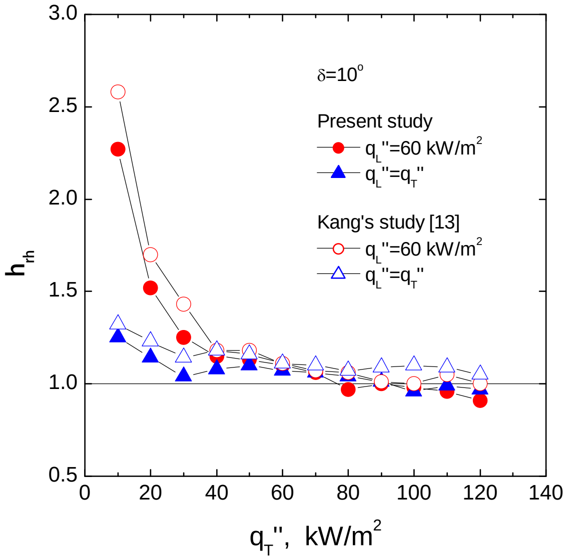

Fig. 5. Comparison of present data with published results.

To identify the asymmetry effects on heat transfer the present experimental data were compared to the results for the symmetry tube array [13] as shown in Fig. 5. The heat transfer coefficients of the upper tube were divided by that of the single horizontal tube for the comparison of equality, and the results were designated as h_{rh}. The tendencies of the two cases are very similar each other. However, the values of h_{rh} for the present study are slightly smaller than that of the symmetry tubes. This is because of the difference of the overlapping length of the tubes. If the upper tube is inclined and the lower tube is horizontal, the projection length of the upper tube on the lower tube can be calculated as $L\cos\delta$. Therefore, $L(1-\cos\delta)$ of the lower tube is not overlapping with the upper tube. Since the flow generated by the lower tube moves upward, this non-overlapping length does not fully contribute to the heat transfer enhancement of the upper tube.

4. Conclusions

The combined effects of the included angle and the heat flux of the lower tube on heat transfer of the upper tube were investigated for the tube array having horizontal lower tube. The increase of δ eventually decreases the heat transfer coefficient. The enhancement due to the lower tube is clearly observed at the heat fluxes where the convective effect is dominant. The present study and the published results show a similar tendency. However, the values of h_{rh} for the present study are slightly smaller than the published results.

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