Pool Boiling Heat Transfer of V-Shape Tubes Having Horizontal Upper 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]. 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 very important.

Many researchers have investigated effects of a tube pitch on heat transfer enhancement [3-6]. 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 [7]. 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 [8].

It was explained that the major influential factor is the convective effects due to the fluid velocity and the rising bubbles [9]. Ustinov et al. [10] investigated effects of the heat flux of lower tube (q''_L) on pool boiling of the upper tube and identified that the increase in q''_L 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 [11]. The passive condensers adopted in SWR1000 and APR+ have V-type tubes [1,2] in vertical alignment. Kang [11] 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+. The rate of heat transfer is affected due to the tube shape asymmetry. Kang [12] also published some results for the asymmetry V-shape tubes having a lower horizontal tube.

In this paper, another asymmetry type which having a horizontal upper tube is investigated to identify the effects of the included angle. 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.

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) and 400mm length (L). The included angle was regulated by adjusting the lower tube. The upper tube is situated horizontally. The angle between the tubes was changed from 2° to 24°. The test matrix is shown in Table 1. q''_T is the heat flux of the upper tube surface.

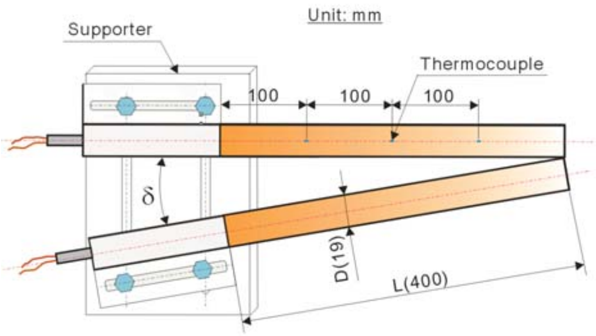

Fig. 1. Schematic diagram of test section.

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

The tube outside was instrumented with six T-type sheathed thermocouples. The thermocouples were brazed on the sides of the tube. The water temperatures were measured with six sheathed T-type thermocouples that placed vertically. 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 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 of the upper tube with input power.

The uncertainties of the experimental data were calculated from the law of error propagation [11]. 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%. 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 47.6% (from 4.7 to 6.2°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 the enhancement in heat transfer is clearly observed at low or moderate heat fluxes. When q''_T >100kW/m^2 the curves for $q''_L \neq$ 0kW/m^2 converge to the curve for the single tube.

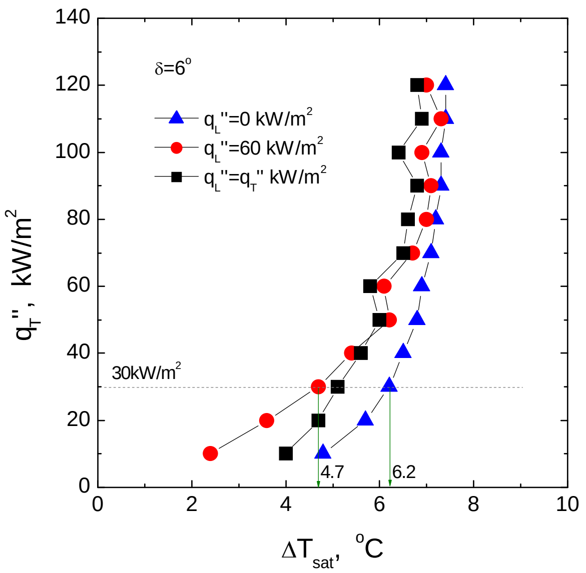

Fig. 2. Plots of q''_T versus ΔT_{sat} .

Figure 3 shows variations in the bundle effect against the heat flux of the upper tube for δ =18°. As the heat flux of the upper tube increases from 10 to 120kW/m^2, the bundle effect decreases dramatically from 1.94 to 1.06 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 q''_T >60kW/m^2, regardless of q''_L .

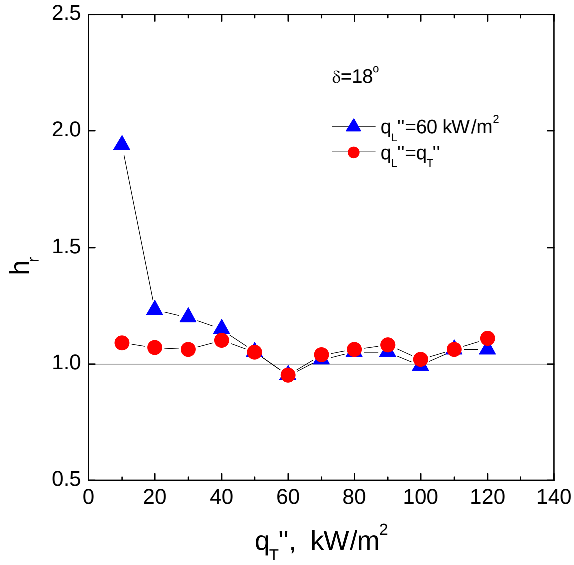

Fig. 3. Variations in bundle effect for δ =18°.

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 [6]. The intensity of the convective flow is increased as q''_L increases. 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.

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 60kW/m^2 are shown in Fig. 4. To identify the asymmetry effects on heat transfer the present experimental data were compared to the published results. In the figure, LH and UH mean lower horizontal and upper horizontal, respectively. The heat transfer coefficients decrease as δ increases up to 10°. The heat transfer coefficients are slightly increasing or decreasing depending on the geometry as δ >10°. Throughout the included angles h_b for the symmetry case is greater than the other cases. The UH case shows similar tendency comparing to the LH case. However, enhanced heat transfer is observed for UH case.

This is because of the difference of the overlapping length of the tubes. The upper tube is affected by the lower tube through the tube length regardless of δ for the symmetry case. However, part of the upper tube is not directly affected by the lower one for the asymmetry cases. If 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. If the upper tube is horizontal and the lower tube is inclined like present study, the upcoming flow get integrated in the overlapped length. This is the major cause of the heat transfer enhancement. However, some part of the upper tube is not overlapping with the projection length. 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. This is the cause of the heat transfer deterioration comparing to the symmetry case.

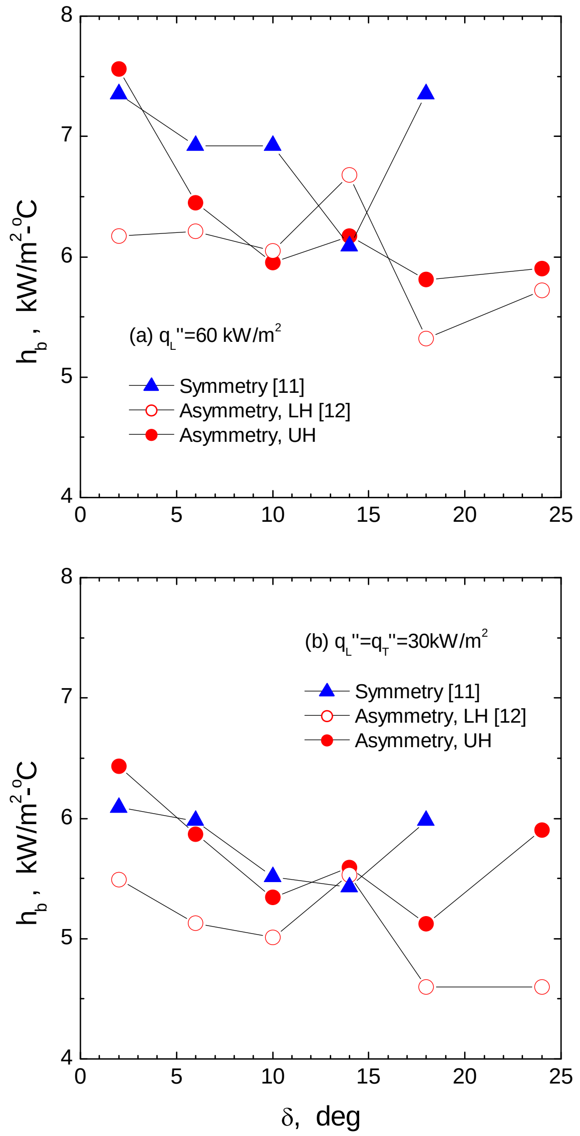

Fig. 4. Plots of h_b versus δ at q''_T =30kW/m^2.

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 [11]. 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 [11], a slight increase in heat transfer is observed at the larger included angles.

4. Conclusions

The effects of the included angle and the heat flux of the lower tube on heat transfer of the upper tube were investigated for the V-shape tubes having a horizontal upper 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_b for the present study are smaller than the symmetry case. However, enhanced heat transfer is observed compared to the lower horizontal case.

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