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Pool Boiling Heat Transfer from Two Horizontal Tubes in Vertical Alignment

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1. Introduction

One of the major issues in pool boiling heat transfer is the bundle effect. 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 [1]. Since heat transfer results differ due to tube geometries, bundle geometries, and liquid type, lots of studies have been carried out for the combinations of those parameters [2,3].

The most effective parameter must be the pitch (P) between tubes. Many researchers have been investigated its effect on heat transfer enhancement for the tube bundles [4-6] and the tandem tubes [7,8]. The heat transfer on the upper tube of the tubes is enhanced compared with the single tube [8]. However, the maximum heat transfer of the upper tube increases [8] or decreases [7] with increasing the tube pitch in pool boiling. Ribatski et al. [5] reported that the effect of the tube spacing on local heat transfer along the tube array was negligible.

The upper tube within tube bundle can significantly increase nucleate boiling heat transfer compared to the lower tubes at moderate heat fluxes. At high heat fluxes these influences disappear and the data merge onto the pool boiling curve of a single tube [9]. It was explained that the major influential factor is the convective effects due to the fluid velocity and the rising bubbles [3].

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. [10] 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.

Summarizing the published results, some parts are still remaining to be investigated in detail. Therefore, the present study is aimed to study the effects of the tube pitch and the heat flux of the lower tube on heat transfer enhancement of the tandem tubes, arranged one above the other in the same vertical plane.

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 tube is a resistance heater made of a very smooth stainless steel tube of 19 mm diameter (D). The pitch was regulated by adjusting the space between the tubes, which were positioned one above the other and were assembled using bolts and nuts to the supporter. The values of the tube pitches and the heat fluxes of the lower tube are listed in Table 1. q''_T is the heat flux of the upper tube surface.

Table 1. Test Matrix

P, mm	P/D	q''_L, kW/m²	q''_T, kW/m²
28.5	1.5	0,30,60,90, q''_T	10-110
38	2	0,30,60,90, q''_T	10-110
47.5	2.5	0,30,60,90, q''_T	10-110
57	3	0,30,60,90, q''_T	10-110
76	4	0,30,60,90, q''_T	10-110
95	5	0,30,60,90, q''_T	10-110
114	6	0,30,60,90, q''_T	10-110

The tube outside was instrumented with six T-type sheathed thermocouples. The thermocouple was brazed on the tube wall. 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.

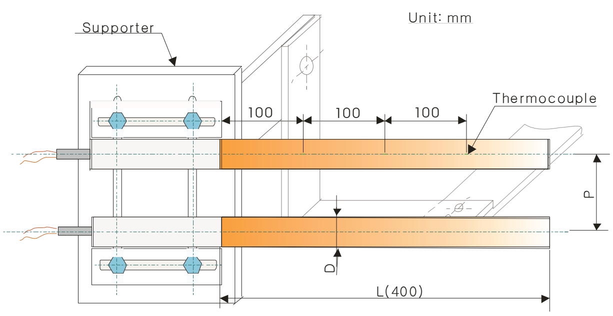

Fig. 1. Schematic diagram of test section.

After the water tank was filled with water until the initial water level reached 1100 mm, 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 [11]. The data acquisition error and the precision limit were counted for the uncertainty analysis of the temperature. The 95 percent confidence 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 some photos of pool boiling for the tandem tubes. Those photos were taken around the upper tube. As shown in the photos relatively larger bubbles are observed on the surface of the upper tube. Two competing heat transfer mechanisms, active liquid agitation and bubble coalescence on the surface, are caused by these bubbles. Liquid agitation enhances heat transfer, especially when the heat flux of the upper tube is low, while the bunch of bubbles on the surface deteriorates heat transfer, in general, at high heat flux regimes.

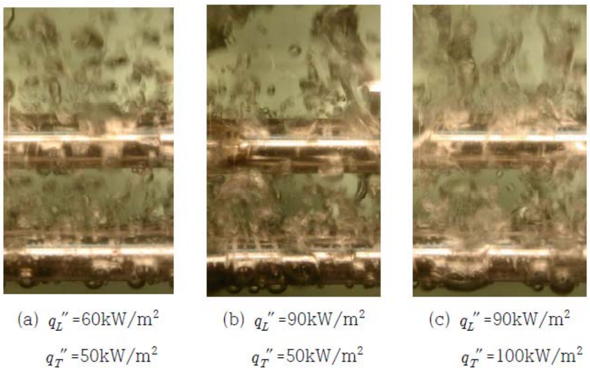

Fig. 2. Photos of pool boiling on tube surfaces.

The variations of the bundle effect ($h_b / h_{b,q_L''=0}$) for the different q_L'' and P/D values are shown in Fig. 3. The heat transfer on the upper tube of the twin tubes is enhanced compared with the single tube. The bundle effect for P/D =1.5 is the maxima when q_T'' ≥30kW/m² regardless of q_L'' value. This tendency is similar to Gupta et al. [7]. However, the tendency changes when $q_L'' \neq q_T''$ and q_T'' is less than 30kW/m². The bundle effect for $P/D \geq 4$ is bigger than that for P/D =1.5. One of the possible explanations for the tendency is the development of turbulence. The bubbles departed from the lower tube need some distance to generate enough turbulent effect, which agitates relevant liquid to increase heat transfer coefficient.

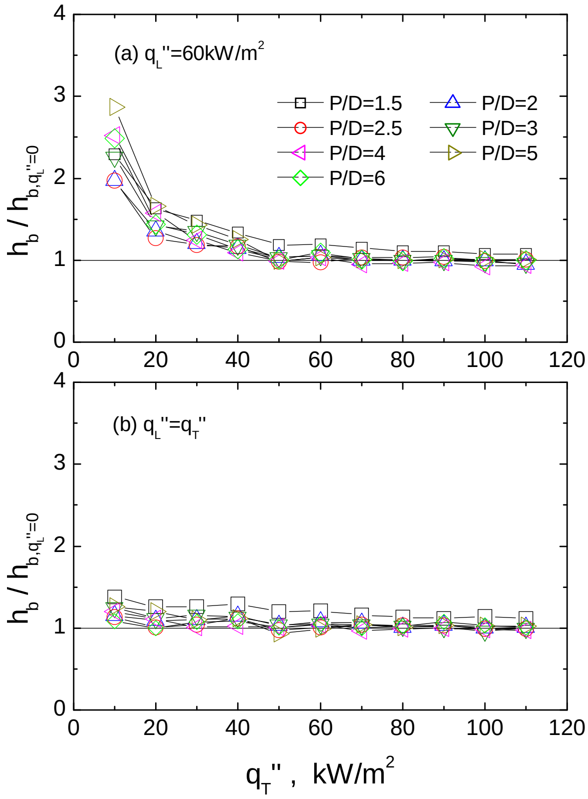

Fig. 3. Variation of bundle effect with q_L'' and P/D .

The bundle effect is clearly observed when $q_L'' > q_T''$ and q_T'' is less than 60kW/m². When q_L'' =60kW/m² (Fig. 3(a)) the values of the bundle effect for P/D =5 are 2.87 and 1, at q_T'' =10 and 80kW/m², respectively. When $q_L'' = q_T''$ (Fig. 3(b)) the values for P/D =5 are 1.26 and 1.01, at the same q_T'' values, respectively. The bundle effect is expected as the convective onflow of bubbles and liquid, rising from the lower tube, enhances the heat transfer on the upper tube [8]. When the heat flux of the upper tube is low the major heat transfer mechanism is convective flow. 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 effects of convective flow decreases and the enhancement in heat transfer decreases.

A total of 308 data points have been obtained for the heat flux versus superheat for various tube pitch and the heat flux of the lower tube. Through the statistical analysis on the experimental data with the help of a computer program (which uses the least square method as a regression technique) a simple equation was determined as $h_b = 0.519 q_T''^{\,0.647} q_L''^{\,0.079} / (P/D)^{0.048}$.

In the above equation, the dimensions for h_b and q'' are kW/m²-ºC and kW/m². Figure 4 shows a comparison of the measured heat transfer coefficient from experiments and the calculated heat transfer coefficient by the above equation. The suggested empirical correlation well predicts the experimental data within ±10% error band, with some exceptions from the fitted data of the above equation. The scatter of the present data is of similar size to that found in other existing pool boiling data.

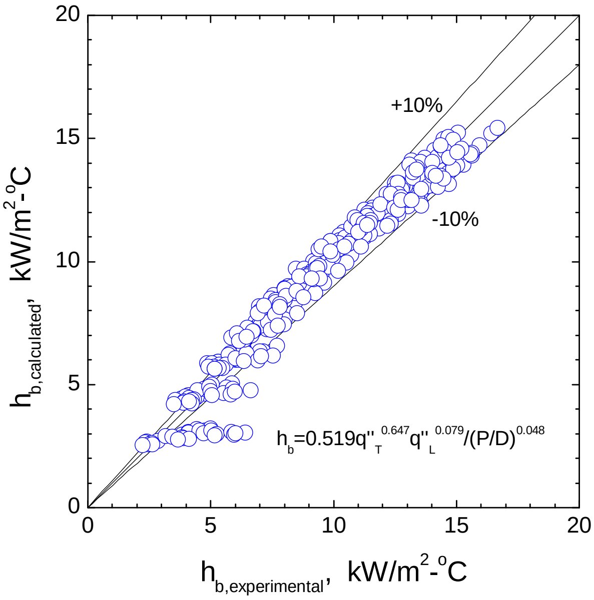

Fig. 4. Comparison of experimental data with calculated heat transfer coefficients.

4. Conclusions

The bundle effect was investigated for the tandem tubes in vertical alignments. The variations of the tube pitch and the heat flux of the lower tube change the bundle effect much. In general, the maximum heat transfer of the upper tube decreases with increasing the tube pitch except q''_T is less than 30kW/m^2 and $q''_L \neq q''_T$. The presence the lower tube enhances the bundle effect much. The bundle effect is clearly observed when $q''_L > q''_T$ and q''_T is less than 60kW/m^2.

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