Suggestion of a New Empirical Correlation to predict Pool Boiling Heat Transfer on Tandem Tubes

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1. Introduction

The mechanism of pool boiling heat transfer has been studied extensively for the several decades since it is closely related with the thermal design of more efficient heat exchangers. One of the major issues is the bundle effect (h_r), which 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]. Most studies were focused on the bundles consisting of many tubes for application to a flooded evaporator [2-4].

Along with the tube spacing, its location is also of interest. Many researchers have been investigated the effect of tube spacing on heat transfer 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 coefficient of the upper tube decreases [7], increases [8], or negligible [5] with increasing tube pitch (P) in pool boiling. According to Ribatski et al. [5] the spacing effects on the heat transfer became relevant as the tubes come closer to each other at the low heat fluxes.

The effect of tube array on heat transfer enhancement was also studied for application to the flooded evaporators [9,10]. The upper tube within a 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 [11].

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. Kumar et al. [12] carried an experimental study and developed a model to predict the heat transfer coefficient of individual tube in a multi-tube row and the bundle heat transfer coefficient. Ustinov et al. [13] investigated effects of the heat flux of lower tube on pool boiling of the upper tube. 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 previous results it can be stated that heat transfer coefficients are highly dependent on the tube geometry and the heat flux of the lower tube. As shown in Table 1 most published studies were for the tandem tubes in a vertical column arrangement. In general, tubes are not in a vertical plane. Therefore, the present study is focused on the quantification of the combined effects of the tube pitch and the elevation angle (θ) of the tubes and the heat flux of the lower tube on pool boiling heat transfer on tandem tubes. To the present author's knowledge, no results on this effect have as yet been published.

Table 1. Summary of Published Results

Author	Liquid	Tube	θ	P/D
Hahne et al. [8]	R11	finned type (19fpi, 26fpi)	90°	1.05, 1.3, 3.0
Gupta et al. [6]	distilled water	smooth	90°	1.5, 3.0, 4.5, 6.0
Ribatski et al. [5]	R123	smooth	90°	1.32, 1.53, 2.0
Ustinov et al. [13]	R134a FC-3284	microstructure	90°	1.5

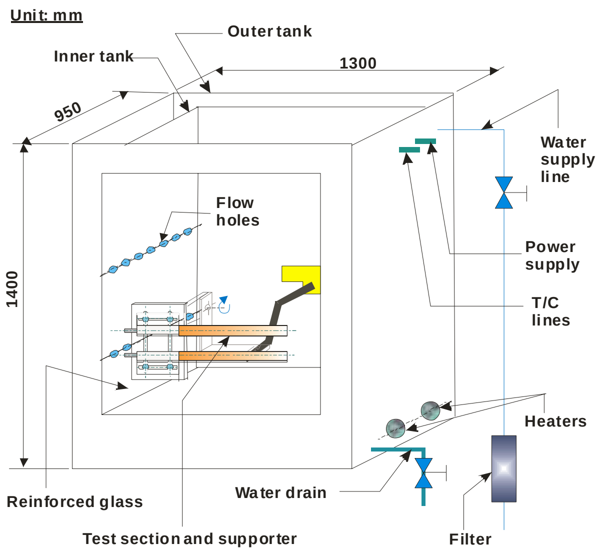


Fig. 1. Schematic of experimental apparatus.

2. Experiments

For the tests, the assembled test section 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. 1. 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. The surface of the tube was finished through a buffing process to have a smooth surface. The surface roughness is R_a =0.15µm.

The pitch was regulated from 28.5 to 114 mm by adjusting the space between the tubes. The elevation angle of the tubes was varied from the horizontal position (0°) to the vertical position (90°) in steps of 15°. The heat flux of the lower tube was (1) set a fixed values of 0, 30, 60, and 90 kW/m^2 or (2) varied equal to the heat flux of the upper tube (q''_T).The values of the tube pitches, elevation angles, and the heat fluxes of the lower tube are listed in Table 2 and the schematic of the tube arrangement is shown in Fig.2.

Table 2. Test Matrix

P/D	θ, deg	q''_L , kW/m²	q''_T , kW/m²
1.5	90	0,30,60,90, q''_T	0-110
2	90	0,30,60,90, q''_T	0-110
2.5	90	0,30,60,90, q''_T	0-110
3	90	0,30,60,90, q''_T	0-110
4	90	0,30,60,90, q''_T	0-110
5	90	0,30,60,90, q''_T	0-110
6	90	0,30,60,90, q''_T	0-110
1.5	0	0,30,60,90, q''_T	0-120
1.5	15	0,30,60,90, q''_T	0-120
1.5	30	0,30,60,90, q''_T	0-120
1.5	45	0,30,60,90, q''_T	0-120
1.5	60	0,30,60,90, q''_T	0-120
1.5	75	0,30,60,90, q''_T	0-120
1.5	90	0,30,60,90, q''_T	0-120

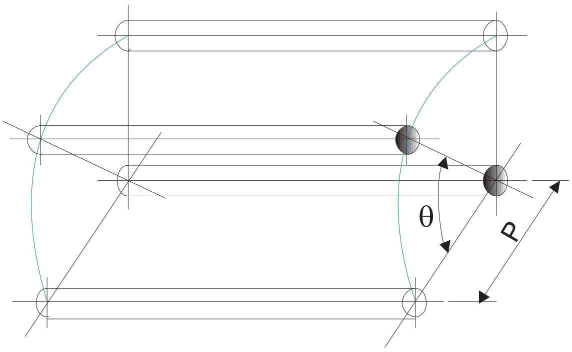


Fig. 2. Schematic of tube arrangement.

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 tube outside was instrumented with six T-type sheathed thermocouples brazed on the tube wall. The water temperatures were measured with six sheathed thermocouples. 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.

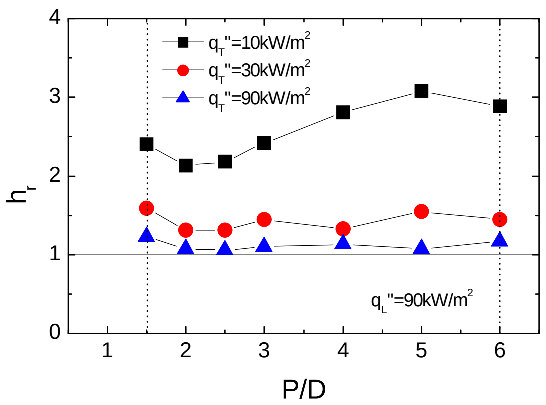
The uncertainties of the experimental data were calculated from the law of error propagation [14]. The data acquisition error and the precision limit were counted for the uncertainty analysis of the temperature. The 95 percent confidence uncertainty of the measured temperature had the value of ±0.11 °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

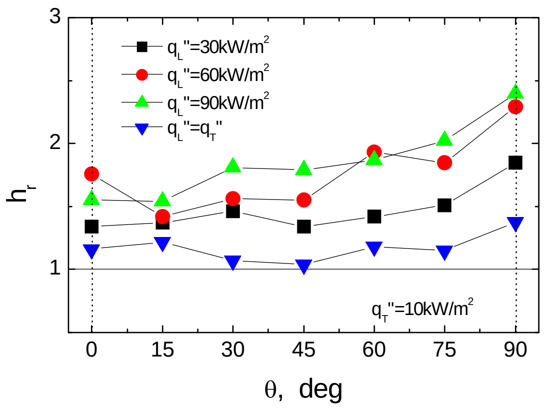
The variations of the bundle effect for the different P/D and θ are shown in Fig. 3 for the different heat fluxes. The heat transfer on the upper tube of the twin tubes is enhanced compared with the single tube. The bundle effect is clearly observed when $q''_L > q''_T$ and q''_T is at low heat fluxes. 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 portion of the liquid convection gets decreased and, accordingly, the enhancement in heat transfer gets disappeared.

The increase in P/D decreases the bundle effect when $q''_L = q''_T$. The bundle effect is clearly observed when $q''_L > q''_T$. If the difference between the two heat fluxes is large the tendency is different from the results for $q''_L = q''_T$. The increase in P/D decreases, increases, and decreases the value of h_r . The bundle effect for q''_T = 10kW/m^2 is the maxima when P/D =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. This effect is strongly observed at the heat fluxes where the convective effect is dominant. Another related cause is the static pressure of the liquid. The size of the departed bubbles gets increased while moving upward due to the decrease of the static pressure. The big size bubbles generate active liquid agitation which enhances heat transfer.

To identify the bundle effect the ratios of $h_b / h_{b,q_L''=0}$ were obtained for the different q_L'' as the elevation angle changes from 0° to 90°. Results for the q_T'' =10 kW/m^2 are shown in Fig. 3(b). The increase of both q_L'' and θ results in heat transfer enhancement. The increase in the bundle effect is clearly observed at $\theta \geq$ 45°. As the heat flux of the lower tube increases, the bundle effect decreases dramatically. The major reason of the heat transfer enhancement on the upper tube is due to the convective flow and liquid agitation caused by the lower tube. The intensity of the effects is magnified when the upper tube is just above the lower tube. Since the mixed flow of bubble and liquid goes upward due to the buoyancy, the decrease in the elevation angle decreases the effects of the convective flow on heat transfer. This decreases the bundle effect.



(a) Plots of h_r vs P/D



(b) Plots of h_r vs θ

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

Through the experiments, a total of 644 data points have been obtained for the heat flux versus the wall superheating for various combinations of pitch, elevation angle, and heat fluxes. Although it is not realistic to obtain any general theoretical correlation for heat transfer coefficients in nucleate boiling since it contains inherent unidentified uncertain parameters, we continue the development of the correlation nevertheless. This is because the quantification of the experimental results could broaden its applicability to the thermal designs. To take account of effects of the parameters, a simple correlation is sought and, as a result, an empirical correlation has been obtained using present experimental data and the statistical analysis computer program (which uses the least square method as a regression technique) as follows:

$$h_r = \frac{h_b}{h_{b,q_L''=0}} = A q_L''^{(B/q_T'')} \qquad (1)$$

$$A = 0.965(P/D)^{-0.0007\theta},$$

$$B = 1.269(P/D)^{0.005\theta}.$$

In the above equations, the dimensions for q'', and θ are kW/m², and deg, respectively. Apparently the correlations only apply for the testing pressure and parameters.

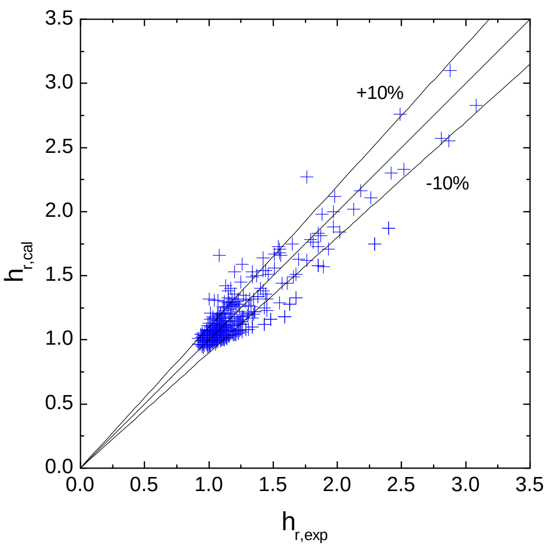


Fig. 4. Comparison of experimental data to calculated bundle effects.

To confirm the validity of the correlation the statistical analyses on the ratios of the measured and the calculated heat transfer coefficients (i.e., $h_{r,\exp}/h_{r,cal}$) have been performed. The mean and the standard deviation are 1.01 and 0.08, respectively. A comparison between the bundle effect from the tests ($h_{r,\exp}$) and the calculated value ($h_{r,cal}$) by Eq. (1) is shown in Fig. 4. The newly developed correlation predicts the present experimental data within ±10 %, with some exceptions.

To identify the applicability of the present correlation to the published results listed in Table 1, the predicted values and the experimental data are plotted as shown in Fig. 5. The present correlation predicts the published data within ±20 %, with some exceptions. The scatter of the present data is of similar size to that found in other existing pool boiling data. Since the published data set was obtained for the different liquid and surface combinations, the present correlation could be applied for the calculation of the bundle effect of tandem tubes regardless of the liquid type and tube surface condition.

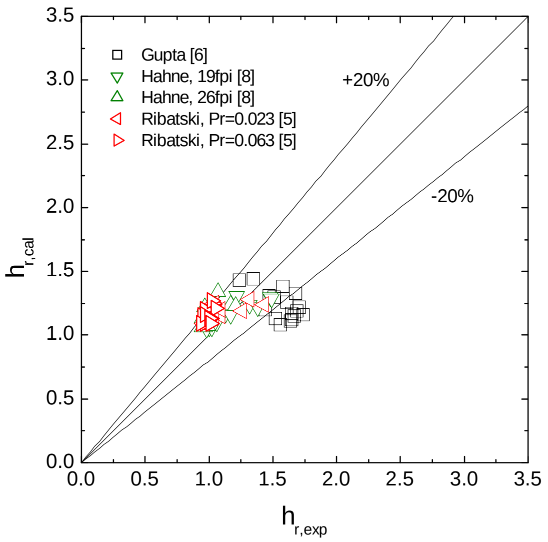


Fig. 5. Comparison of published experimental data to calculated bundle effects by Eq. (1).

4. Conclusions

The bundle effect was investigated for the variations of tube pitch, elevation angle, and the heat flux of the lower tube for application to the tandem tubes. The bundle effect is clearly observed when $q''_L > q''_T$. The decrease in P/D and increase in θ increases the bundle effect. The newly developed correlation predicts the experimental data within ±10 %.

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