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Development of Empirical Correlation to Calculate Pool Boiling Heat Transfer of Tandem Tubes

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1. Introduction

Pool boiling is closely related to the design of passive type heat exchangers, which have been investigated in nuclear power plants to meet safety functions in case of no power supply. One of the major issues in the design of a heat exchanger is the heat transfer in a tube bundle. The passive condensers adopted in SWR1000 and APR+ has U-type tubes [1,2]. The heat exchanging tubes are in vertical alignment. For the cases, the upper tube is affected by the lower tube.

Since heat transfer is closely related to the conditions of tube surface, bundle geometry, and liquid, lots of studies have been carried out for the several decades to investigate the combined effects of those factors on pool boiling heat transfer [3,4]. One of the most important parameters in the analysis of a tube array is the pitch (P) between tubes. Many researchers have been investigated its effect on heat transfer enhancement for the tube bundles [5-7] and the tandem tubes [6,8,9]. The effect of a tube array on heat transfer enhancement was also studied for application to the flooded evaporators [10-13].

Cornwell and Schuller [14] studied the sliding bubbles by high speed photography to account the enhancement of heat transfer observed at the upper tubes of a bundle. The study by Memory et al. [15] shows the effects of the enhanced surface and oil adds to the heat transfer of tube bundles. They identified that, for the structured and porous bundles, oil addition leads to a steady decrease in performance. The flow boiling of n-pentane across a horizontal tube bundle was investigated experimentally by Roser et al. [16]. They identified that convective evaporation played a significant part of the total heat transfer. The fouling of the tube bundle under pool boiling was also studied by Malayeri et al. [17]. They identified that the mechanisms of fouling on the middle and top heater substantially differ from those at the bottom heater.

The heat transfer on the upper tube is enhanced compared with the single tube [10]. 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 [18]. The upper tube within a tube bundle can significantly increase heat transfer compared to the lower tubes at moderate heat fluxes. At high heat fluxes these influences disappear and the data merge the pool boiling curve of a single tube [13]. It was explained that the major influencing factor is the convective effects due to the fluid velocity and the rising bubbles [4]. For tandem tubes having an equal heat flux, the greatest heat transfer coefficient of the upper tube decreases [8], increases [9], or negligible [6] with increasing tube pitch in pool boiling. Some possible explanations for the discrepancy are due to the liquid and the difference in geometric conditions of the test section and the pool [19].

Ribatski et al. [6] performed an experiment with R123 and smooth brass tubes of 19.05 mm outer diameter (D). Through the investigation, the effects of reduced pressure (p_r) and tube pitch were studied. They suggested an empirical correlation to predict effects of the reduced pressure and the location (N) of a tube in a horizontal tube bundle. It was identified that the effect of tube spacing on the local heat transfer coefficient along the tube array was negligible. At low heat fluxes, the tube positioning shows a remarkable effect on the heat transfer because of the free convection. However, at high heat fluxes the effect of natural convection is negligible and the effects of bubbles become dominant. According to Ribatski et al. [6] the spacing effects on the heat transfer became relevant as the tubes come closer to each other due to bubble confinement between consecutive tubes.

Gupta et al. [8] investigated the effect of tube pitch on pool boiling of two tubes placed one above the other. They used a stainless steel tube of commercial finish having 19.05 mm outer diameter and the distilled water at 1 bar. They found that the heat transfer coefficients of the upper tube were increased as the pitch distance decreased due to the larger number of bubbles intercepted by the upper tube when the pitch was lowered.

Hahne et al. [10] used finned type copper tubes submerged under R11 at 1 bar. The tube pitch was varied between P/D=1.05 and 3.0. They found that the largest heat transfer of the upper tube increased with increasing tube pitch. This is expected as the convective flow of bubbles and liquid, rising from the lower tube, enhances the heat transfer on the upper tube. However, as the heat flux increases the heat transfer of the upper tube decreases with increasing tube pitch.

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. Kumar et al. [20, 21]

carried an experimental study using the combination of distilled water and two horizontal reentrant cavity copper tubes. They used a fixed spacing and developed a model to predict the heat transfer coefficient of individual tube in a multi-tube row and the bundle heat transfer coefficient. The model contains the heat flux of the lower tube. Ustinov et al. [22] also investigated effects of the heat flux of the 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 superheating (ΔT_{sat}) of the upper tube.

Kang [19, 23] studied the combined effects of tube pitches, elevation angles (θ), and heat fluxes of a lower tube. The parameters were changing pool boiling heat transfer of the upper tube. Kang [23] also suggested an empirical correlation containing the pitch, elevation angle, and the heat flux of the lower tube to predict pool boiling heat transfer of the tandem tubes. The correlations suggested by the previous researchers are listed in Table. 1 and a schematic diagram of the tandem tubes are shown in Fig. 1.

Table 1. Published Correlations for Tandem Tubes

Author	Correlations	Remarks
Kumar et al. [20]	$h_r = 6.27 q_L''^{0.3} q_T''^{-0.45}$	- P/D =0.5 - θ =90° - ϕ =0° - p =35.36~97.5kPa - distilled water
Ribatski et al. [6]	$h_r = 1 + 0.345 C_A p_r^{-1.4} q_T''^{-1} e^{-0.37 p_r^{-0.4} [\ln(q_T''/(C_q p_r^{-0.7}))]^2}$ $C_A = 160 - 85.2 e^{-0.3N}$ $C_q = 65 + 1200 e^{-0.3N}$	- P/D =1.32,1.53,2.0 - θ =90° - ϕ =0° - p_r =0.023,0.063 - R123
Kang [23]	$h_r = A q_L''^{B/q_T''}$ $A = 0.965(P/D)^{-0.0007\theta}$ $B = 1.269(P/D)^{0.005\theta}$	- P/D =1.5~6 - θ =0~90° - ϕ =0° - p =1atm - boiled water

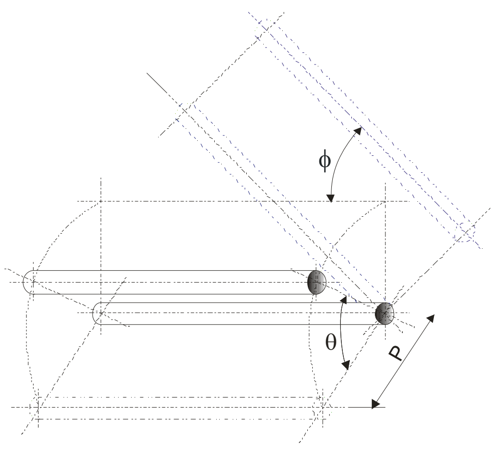

Fig. 1. Schematic of tube arrangement.

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. Most published correlations are for application to the tandem tubes in horizontal position as shown in Table 1. In industry, some heat exchangers have inclined tube bundles like the passive condensation heat exchanger (PCHX) adopted in APR+ [2]. According to the published results, it is identified that the effects of the inclination angle on pool boiling are closely related with the geometries [24]. Therefore, the present study focuses on the quantification of the combined effects of the tube pitch, the elevation angle, and the inclination angle (ϕ) of the tubes and the heat flux of the lower tube on pool boiling heat transfer on tandem tubes. The objective of the study is to improve Kang's previous correlation [23] with including the inclination angle into the correlation. For the purpose, experiments to obtain the effects of the inclination angle were performed and a new correlation was suggested. To the present author's knowledge, no results of this effect have as yet been published.

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. 2. The heat exchanging tube is a resistance heater made of a very smooth stainless steel tube of 19 mm outside diameter and 400 mm heated length (L). The tube was finished through a buffing process to have a smooth surface (roughness: R_a =0.15μm).

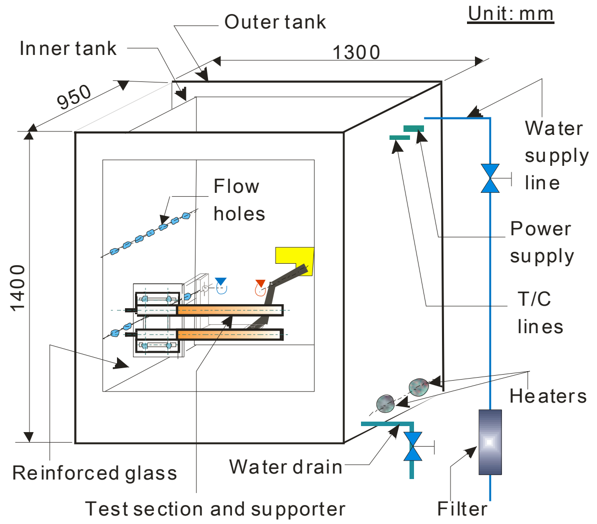

Fig. 2. Schematic of experimental apparatus.

The pitch was regulated from 28.5 to 114 mm by adjusting the space between the tubes. The elevation angle and the inclination angle of the tubes were varied from the horizontal position (0°) to the vertical position (90°) in steps of 15°. The inclination angle and the elevation angle were varied by rotating the assembled tube assembly. The heat flux of the lower tube was (1) set fixed values of 0, 30, 60, and 90 kW/m^2 or (2) varied equal to the heat flux of the upper tube.

The water tank was filled with the filtered tap water until the first 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 (100 °C since all tests were done at atmospheric pressure), the water was then boiled for 30 minutes to remove the dissolved air. The temperatures of the tube surfaces (T_W) were measured when they were at steady state while controlling the heat flux on the tube surface with the input power.

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 brazing metal is a kind of brass and the averaged brazing thickness is less than 0.1 mm. The temperature decrease along the brazing metal was calibrated by the one dimensional conduction equation. Since the thermal conductivity of the brass is nearby 130W/m-ºC at 110ºC [25], the maximum temperature decrease through the brazing metal is 0.08ºC at 110kW/m^2. The value was calculated by the product of the heat transfer rate and the thermal resistance. The measured temperatures were calibrated considering the above error. 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. 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:

$$q''_T = \frac{VI}{\pi DL} = h_b \Delta T_{sat} = h_b (T_W - T_{sat}) \tag{1}$$

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_{sat} represent the measured temperatures of the tube surface and the saturated 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 [26]. 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 $q''_T / \Delta T_{sat}$, 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

Through the experiments, a total of 1,225 data points have been obtained for the heat flux versus the wall superheating for various combinations of pitch, elevation angle, and heat fluxes as listed in Table. 2.

Table 2. Experimental Data for Correlation Development

P/D	θ, deg	ϕ, deg	q''_L, kW/m²	q''_T, kW/m²	Number of data (CD*)
1.5	90	0	0,30,60,90, q''_T	10-110	55(44)
2	90	0	0,30,60,90, q''_T	10-110	55(44)
2.5	90	0	0,30,60,90, q''_T	10-110	55(44)
3	90	0	0,30,60,90, q''_T	10-110	55(44)
4	90	0	0,30,60,90, q''_T	10-110	55(44)
5	90	0	0,30,60,90, q''_T	10-110	55(44)
6	90	0	0,30,60,90, q''_T	10-110	55(44)
1.5	0	0	0,30,60,90, q''_T	10-120	60(48)
1.5	15	0	0,30,60,90, q''_T	10-120	60(48)
1.5	30	0	0,30,60,90, q''_T	10-120	60(48)
1.5	45	0	0,30,60,90, q''_T	10-120	60(48)
1.5	60	0	0,30,60,90, q''_T	10-120	60(48)
1.5	75	0	0,30,60,90, q''_T	10-120	60(48)
1.5	90	0	0,30,60,90, q''_T	10-120	60(48)
5	90	0	0,30,60,90, q''_T	10-120	60(48)
5	90	15	0,30,60,90, q''_T	10-120	60(48)
5	90	30	0,30,60,90, q''_T	10-120	60(48)
5	90	45	0,30,60,90, q''_T	10-120	60(48)
5	90	60	0,30,60,90, q''_T	10-120	60(48)
5	90	75	0,30,60,90, q''_T	10-120	60(48)
5	90	90	0,30,60,90, q''_T	10-120	60(48)

* CD means data for correlation development. The experimental data for q''_L =0 are used to calculate the bundle effects (h_r).
* Experimental data for correlation development=980points
* Total number of experimental data=1225points

Table 3. Results of Statistical Analyses

Author	Mean	Standard deviation
Kumar et al. [20]	3.25	0.71
Ribatski et al. [6]	1.46	0.72
Kang [23]	1.02	0.15

The experimental data were compared with the calculated results by the published correlations listed in Table 1 to investigate the applicability of them to this study. The results of 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 and listed in Table 3. Figure 3, 4, and 5 show the results of the comparison. It is identified that the calculated bundle effects by Kumar et al. [20] and Ribatski et al. [6] very much over predict the present experimental data. Kang's correlation [23] is acceptable though. However, it is necessary to reduce the range of the deviation in order to increase the accuracy of the correlation.

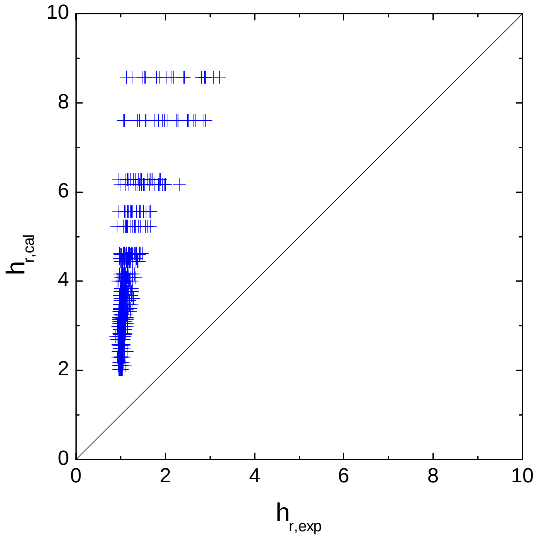

Fig. 3. Comparison of experimental data with Kumar et al.'s correlation [20].

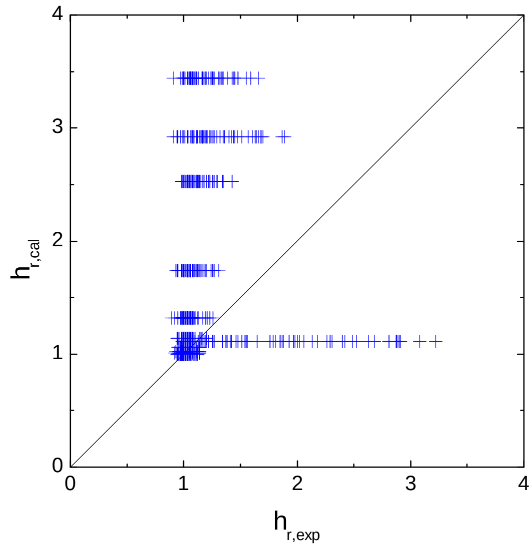

Fig. 4. Comparison of experimental data with Ribatski et al.'s correlation [6].

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:

$$h_r = \frac{h_b}{h_{b,q''_L=0}} = A q''^{\,(B/q''_r)}_L \qquad (2)$$

$$A = \frac{(P/D)^{-0.0007\theta}}{1.0448 - 0.0016\phi},$$

$$B = \frac{(P/D)^{0.005\theta}}{0.7569 + 0.0003e^{0.1434\phi}}.$$

In the above equations, the dimension for q''_L is kW/m². The unit of θ and ϕ is deg. Apparently the correlation only applies for the testing pressure and parameters shown in Table 2.

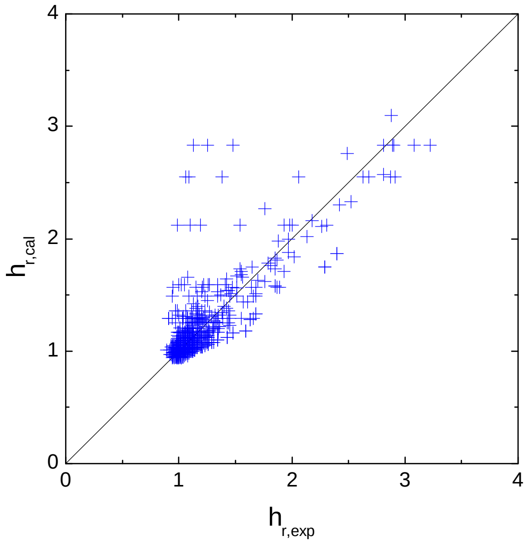

Fig. 5. Comparison of experimental data with Kang's correlation [23].

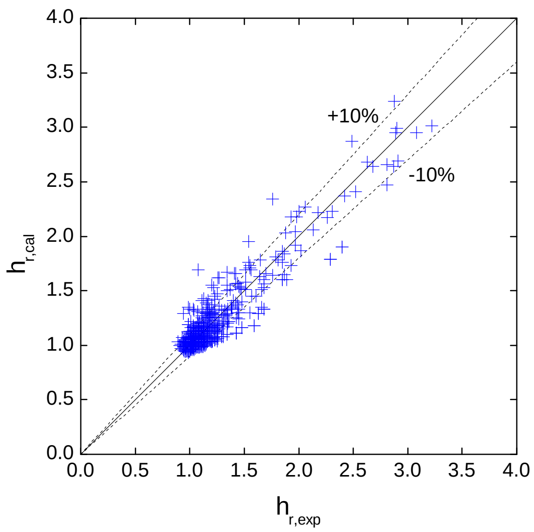

Fig. 6. Comparison of experimental data to calculated bundle effects.

A comparison between the bundle effect from the tests ($h_{r,\exp}$) and the calculated value ($h_{r,cal}$) by Eq. (2) is shown in Fig. 6. 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 1.00 and 0.08, respectively. The newly developed correlation predicts the present experimental data within ±10 %, with some exceptions. As noted by Cornwell and Houston [27], there seems to be some inherent randomness in pool boiling due to the uncertainties associated with nucleation site density, physical conditions of the tube surface, and others. This fact precludes greater accuracy of both theoretical and empirical correlations for heat transfer coefficients in nucleate boiling.

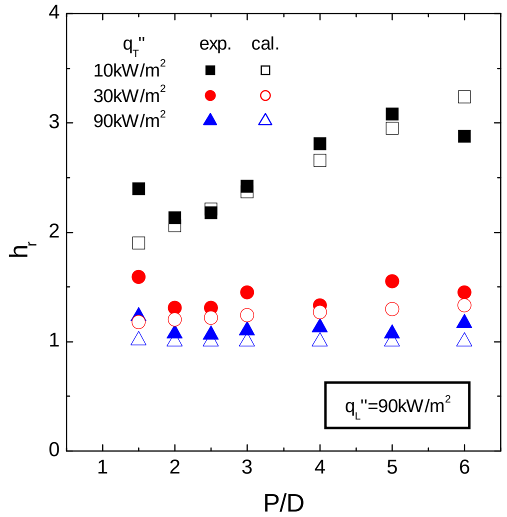

Fig. 7. Plots of h_r against P/D (θ =90°, ϕ =0°).

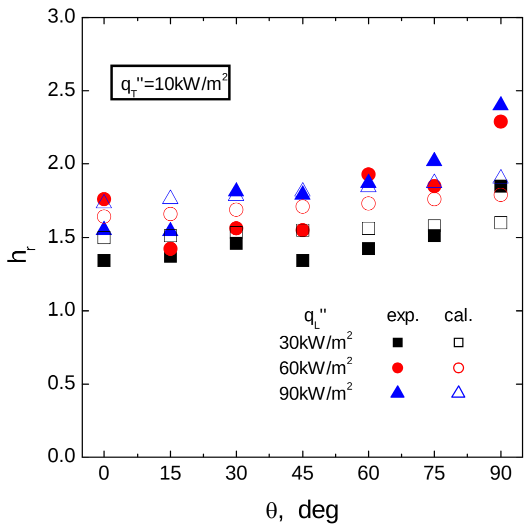

Fig. 8. Plots of h_r against θ (P/D =1.5, ϕ =0°).

To evaluate the suitability of the newly developed correlation, the calculated results were compared to the experimental data. Figure 7 shows the comparison results when the P/D changes from 1.5 to 6. The calculated values by the developed correlation predict the experimental data well. The variation of the bundle effect when the elevation angle changes from 0° to 90° is shown in Fig. 8. Although some discrepancy is observed at θ =90° the overall prediction of the correction is acceptable. Figure 9 shows the variation of the bundle effect due to changes of the inclination angle. The inclination angle ranges from 0° to 90°. As shown in the figure the developed correlation predicts the tendencies and the exact values well. The variation of bundle effect by the heat flux of the lower tube was also evaluated and shown through the figures from 7 to 9. The calculated values by the correlation predict the experimental data within acceptable range.

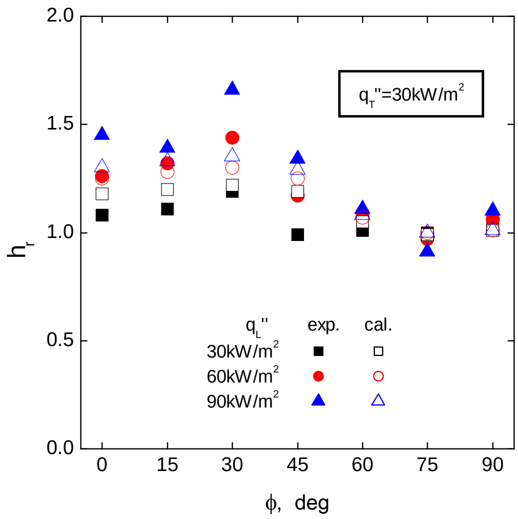

Fig. 9. Plots of h_r against ϕ (P/D =5, θ =90°).

Table 4. Summary of Published Results (θ =90°, ϕ =0°)

Author	Liquid	Tube	P/D
Hahne et al. [10]	R11	finned type (19fpi, 26fpi)	1.05, 1.3, 3.0
Gupta et al. [8]	distilled water	smooth	1.5, 3.0, 4.5, 6.0
Ribatski et al. [6]	R123	smooth	1.32, 1.53, 2.0

To identify the applicability of the present correlation to the published results (Table 4), the predicted values and the experimental data are plotted as shown in Fig. 10. 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.

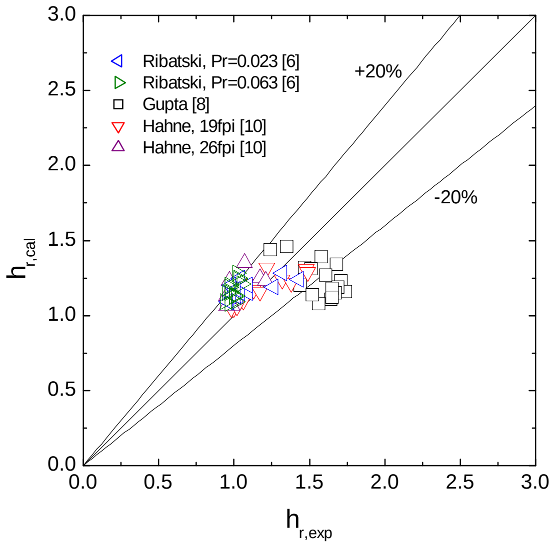

Fig. 10. Comparison of published experimental data to calculated bundle effects by Eq. (2).

4. Conclusions

A new empirical correlation was developed for application to the tandem tubes in the saturated water at atmospheric pressure. The correlation is to evaluate the bundle effect and consists of the tube pitch, elevation angle, inclination angle and the heat flux of the lower tube. The newly developed correlation predicts the experimental data within ±10 %, with some exceptions.

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