Development of Empirical Correlation to Evaluate Pool Boiling Heat Transfer on Inclined Tube Surface

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1. Introduction

Lots of studies have been carried out to investigate the combined effects of geometric parameters of a tube on pool boiling heat transfer. One of the key parameters is the inclination angle (ϕ) of a heated surface. It was identified that the effects of the inclination angle on pool boiling are closely related with the geometries [1].

El-Genk and Bostanci [2] studied the effects of the inclination angle of a copper specimen for application to the design of an electric chip. Stralen and Sluyter [3] performed a test to find out boiling curves for platinum wires. According to Nishikawa et al. [4], the effect of the surface configuration is remarkable at low heat fluxes. Narayan et al. [5] studied the effect of nanoparticles on nucleate pool boiling heat transfer at various surface orientations. Kang [6-8] carried out an experimental study to investigate the pool boiling heat transfer of an inclined tube or an annulus. Recently, Kang [1] studied pool boiling heat transfer on the inside surface of a circular tube.

Summarizing the previous results it can be stated that heat transfer coefficients of a heated specimen are dependent on the inclination angle. However, there are still remaining some ambiguous parts to be studied. Therefore, the present study is aimed at the identification of the combined effects of ϕ and the tube geometry on pool boiling a tube.

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 tubes are resistance heaters made of very smooth stainless steel tubes. The diameter (D, mm)/the heated length (L, mm) of the test tubes are 19/400 and 25.4/ 540, respectively

The inclination angle was changed from 0° to 90° by rotating the supporter. 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 were measured when they were at steady state while controlling the heat flux of the tube with the input power.

The tube outside was instrumented with several T-type sheathed thermocouples (diameter is 1.5 mm) brazed on the sides of the tube wall. The water temperatures were measured with six sheathed T-type thermocouples. To measure and/or control the supplied voltage and current, two power supply systems were used.

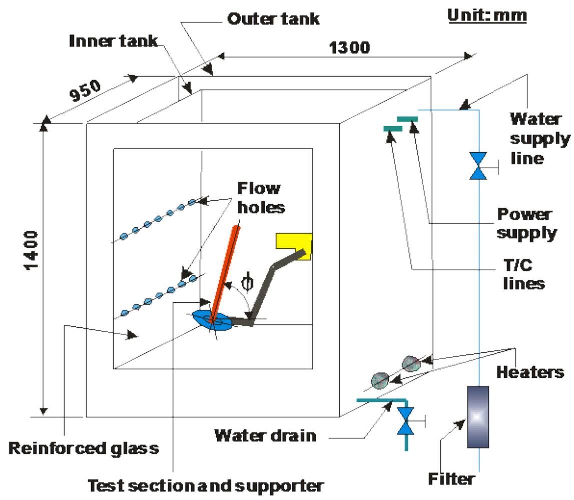

Fig. 1. Schematic of experimental apparatus.

The heat flux from the electrically heated tube surface is calculated from the measured values of the input power as follows:

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

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.

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The uncertainties of the measured temperature and the heat flux are ±0.11 °C and ±0.7%, respectively. The uncertainty of the heat transfer coefficient was calculated through a statistical analysis of the results of $q''_T / \Delta T_{sat}$ and was determined to be ±6%.

3. Results

Figure 2 shows plots of the heat flux versus wall superheat data for the present study (D =19 mm) and published results (D =19.1 mm) [6]. Although two tubes have almost same diameter and have the same surface condition, the tendencies due to the variation of the inclination angle are different from each other. When the tube is in horizontal direction (ϕ =0°) the results are almost same. However, results for the other inclination angles are different. The most appropriate cause is the effect of the tube length. The movement of bubbles along the tube surface is changed due to the inclination angle and, accordingly, the heat transfer is varied.

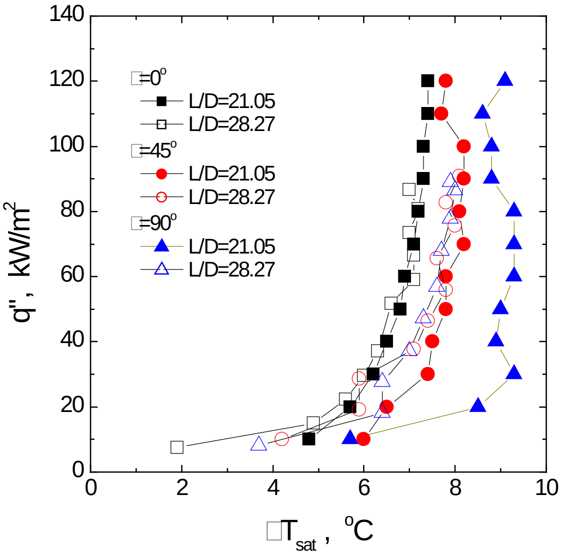

Fig. 2. Plots of q'' versus ΔT_{sat} data for D =19(19.1) mm.

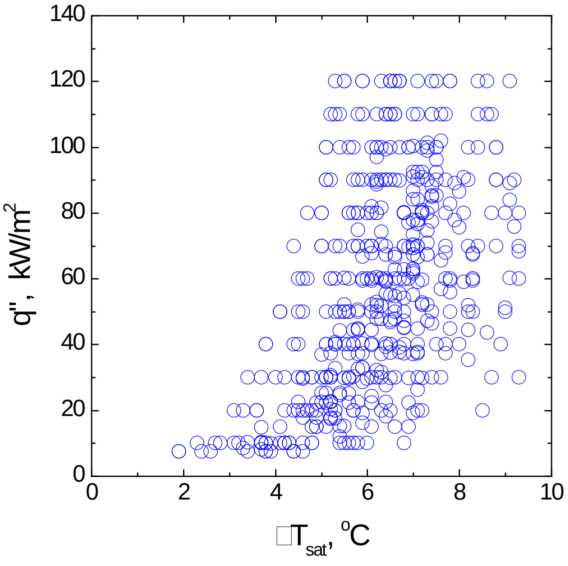

Fig. 3. Plots of experimental data.

To evaluate the effect of inclination angle on pool boiling heat transfer a total of 481 data points were obtained for the heat flux versus the wall superheating for various combinations of diameter and length as listed in Table.1 and were plotted in Fig. 2.

Table 1. Experimental Data for Correlation Development

Reference	ϕ , deg	D , mm	L , mm	L/D	Number of data
[6]	0-90	12.7	540	42.52	63
	0-90	19.1	540	28.27	75
[7]	0-90	25.4	500	19.69	84
	0-90	30	540	18	84
Present	0-90	25.4	540	21.26	91
	0-90	19	400	21.05	84

Table 2. Summary of Published Correlations

Reference	Correlation
Kang [8]	$h_b = \left[0.364\cosh(1.403\phi) - 0.481\phi^2\right] q''^{\frac{1}{0.098(\phi-0.75)^2+1.18}}$
Rohsenow [9]	$q'' = \mu_f h_{fg}\left[\frac{g(\rho_f-\rho_g)}{\sigma}\right]^{\frac{1}{2}}\left(\frac{C_{pf}\Delta T_{sat}}{h_{fg}\Pr_f^s C_{sf}}\right)^3$
Cornwell et al. [10]	$Nu_b = C_{tb}\,\mathrm{Re}_b^{2/3}$, $Nu_b = \frac{h_b D}{k_f}$, $\mathrm{Re}_b = \frac{q''}{h_{fg}}\frac{D}{\mu_f}$
Cooper [11]	$h_b = 55\,p_R^{(0.12-0.2\log_{10}\varepsilon)}(-\log_{10} p_R)^{-0.55} M^{-0.5} q''^{0.67}$

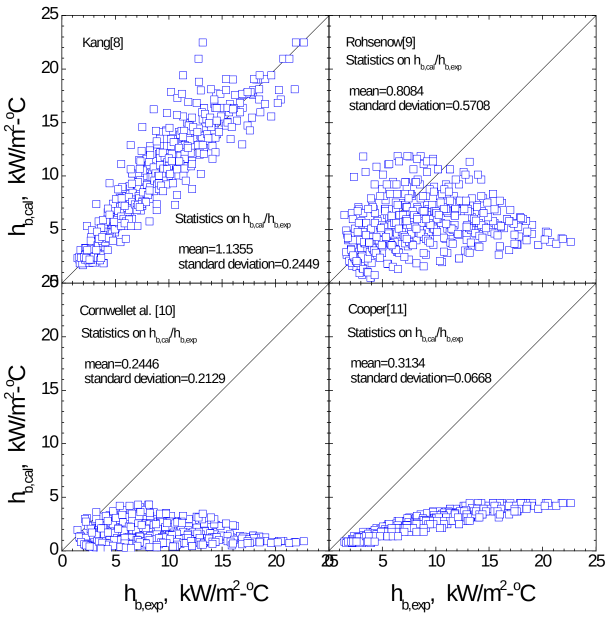

Fig. 4. Comparison of experimental data with published correlations.

The experimental data were compared with the calculated results by the published correlations (Table 2) 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., $h_{b,cal}/h_{b,\exp}$) have been performed and shown in Fig. 4. It is identified that the calculated heat transfer coefficients by Rohsenow [9], Cornwell et al. [10], and Cooper [11] very much under predict the present experimental data. Kang's correlation [8] is acceptable though. However, it is necessary to reduce the range of the deviation in order to increase the accuracy of the correlation. Therefore, a new geometric parameter is newly introduced in this study.

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 [8]. This is because the quantification of the experimental results could broaden its applicability to the thermal designs. To take into account 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:

$$h_b = \left(0.7q'' + \frac{70.5-0.9q''}{32.1+0.01\phi^2}\right)\left(q''\frac{L}{D}\right)^{-0.21} \qquad (2)$$

The dimension for h_b is kW/m²-°C. The unit of q'' and ϕ are kW/m² and deg, respectively. The applicable ranges of the new correlation are L/D =18~42.52, q'' =7~120 kW/m^2, and ϕ =0°~90°.

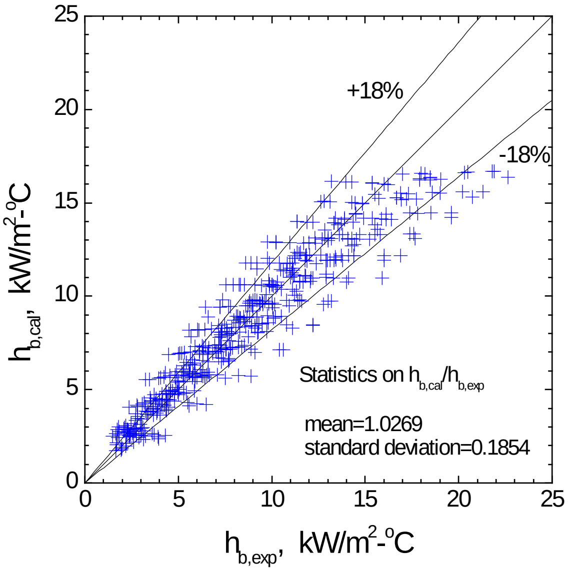

Fig. 5. Comparison of experimental data to calculated heat transfer coefficients by developed correlation.

A comparison between the heat transfer coefficients from the tests ($h_{b,\exp}$) and the calculated value ($h_{b,cal}$) by Eq. (2) is shown in Fig. 5. To confirm the validity of the correlation the statistical analyses on the ratios of the calculated and the measured heat transfer coefficients (i.e., $h_{b,cal}/h_{b,\exp}$) have been performed. The mean and the standard deviation are 1.0296 and 0.1854, respectively. The newly developed correlation predicts the present experimental data within ±18 %, with some exceptions. The scatter of the present data is of similar size to that found in other existing pool boiling data.

4. Conclusions

A new empirical correlation was suggested to obtain the effect of an inclination angle on saturated pool boiling of water at atmospheric pressure. The variations of L/D (18~42.52 mm), inclination angle (0°~90°), and the heat flux of the tube (0~120kW/m^2) were selected as major parameters. The newly developed correlation predicts the experimental data within ±18 %, with some exceptions. The results could be applied for the thermal design of passive safety heat exchangers adopted in the advanced nuclear reactors.

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