Suggestion of Empirical Correlation to Evaluate Effects of Tube Inclination on Pool Boiling Heat Transfer of Various Saturated Liquids

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1. Introduction

Since pool boiling is closely related to the geometry of a heated surface, the effects of geometric parameters on heat transfer have been investigated for the several decades [1]. Through the review of the published results, it can be concluded that one of the key parameters is considering an inclined surface. Many researchers have investigated the effects of the inclination angle (ϕ) of a heated surface for the various combinations of geometries and liquids as listed in Table 1.

Table 1. Summary of Previous Investigations [1]

Author	Geometry	Liquid	Parameters
El-Genk & Bostanci	Flat plate	HFE-7100	ϕ=0°-180°
Stralen & Sluyter	Wire	Water	ϕ=0°,90°
Nishikawa et al.	Flat plate	Water	ϕ=0°-175°
Jung et al.	Flat plate	R-11	ϕ=0°-180° Enhanced surface
Fujita et al.	Parallel plates	Water	ϕ=0°-175° Gap size Flow area confinement
Sateesh et al.	Single tube	Water Ethanol Acetone	ϕ=0°-90° Diameter Surface roughness
Narayan et al.	Single tube	Nano fluid	ϕ=0°-90° Particle concentration
Kang	Single tube Annulus	Water	ϕ=0°-90° Flow confinement
Kang	Tube inside	Water	ϕ=0°-90°

According to Nishikawa et al. [2], the effect of the surface configuration is remarkable at low heat fluxes. Narayan et al. [3] studied the effect of nanoparticles on nucleate pool boiling heat transfer at various surface orientations. An experimental study to investigate the effects of the inclination on pool boiling heat transfer for a tube or an annulus was carried out by Kang [4]. Recently, Kang [5] studied pool boiling heat transfer on the inside surface of a circular tube.

Through the review of the published studies, it can be concluded that the consideration of an inclined surface results in much change in pool boiling heat transfer. Although many researchers have in the past decades investigated the effect of the inclination angle on pool boiling heat transfer along with the effects of pressure and fluid properties, there are still remaining some areas to be identified. One of them is the inclusion of an inclination angle into the correlation. Recently, Kang [1] suggested an empirical correlation including the effect of inclination angle as a factor. In the correlation, the ratio of the length (L) divide by the diameter of a heated tube (D) was newly included as a factor to improve the previous study [4].

However, the correlation suggested by Kang [1] only applicable to the pool boiling of saturated water and the effect of surface roughness (ε) was not counted. Since surface roughness changes heat transfer much, this should be included to improve the accuracy of the correlation. Therefore, the present study is aimed at the development of a new correlation, which includes the surface roughness of the inclined tubes to evaluate pool boiling heat transfer of saturated liquids.

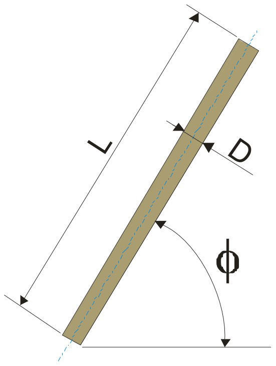

Fig. 1. Schematic of experimental apparatus.

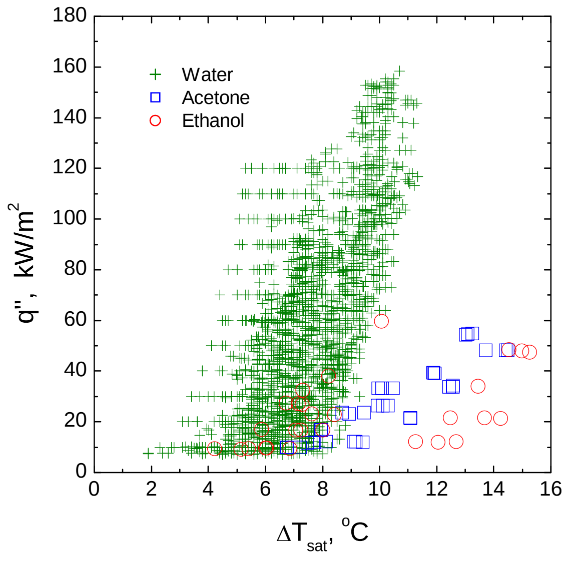

Fig. 2. Plots of experimental data.

2. Correlation of Experimental Data

Through the experiments and a literature survey, a total of 2,105 data points has been obtained for the heat flux versus the wall superheating for various combinations of the inclination angle and the surface roughness as listed in Table 2. The plot of the data is shown Fig. 2. The values of the roughness are the arithmetic mean of all deviations from the center line of the sampling path (i.e., R_a). There is much difference among the data for the same heat flux because of the liquid, surface roughness, and the inclination angle.

Table 2. Experimental Data for Correlation Development

Reference	ϕ, deg	L/D	ε, nm	Liquid	Number of data
[1]	0-90	21.26	150	Water	91
	0-90	21.05	150	Water	84
[6]	0-90	42.52	150	Water	63
	0-90	28.27	150	Water	75
[7]	0-90	19.69	150	Water	84
	0-90	18	150	Water	84
[8]	90	5.25	11.8	Water	20
	90	5.25	48.8	Water	24
	0	11.81	11.8	Water	35
	90	11.81	11.8	Water	44
	0	11.81	48.8	Water	134
	90	11.81	48.8	Water	99
	0	21.43	48.8	Water	94
	90	21.43	48.8	Water	87
	0	27.85	11.8	Water	72
	45	27.85	11.8	Water	65
	90	27.85	11.8	Water	104
	0	27.85	21.6	Water	104
	90	27.85	21.6	Water	127
	0	27.85	48.8	Water	79
	45	27.85	48.8	Water	62
	90	27.85	48.8	Water	110
	0	30.93	11.8	Water	53
	90	30.93	11.8	Water	69
	0	30.93	48.8	Water	66
	90	30.93	48.8	Water	58
[9]	0-90	8.19	80	Water	30
	0-90	8.19	670	Water	12
	0-90	5.21	290	Water	12
	0-90	8.19	80	Ethanol	10
	0-90	8.19	670	Ethanol	9
	0-90	5.21	290	Ethanol	9
	0-90	8.19	80	Acetone	12
	0-90	8.19	670	Acetone	12
	0-90	5.21	80	Acetone	12

The experimental data were compared with the calculated results of the published correlations (Table 3) to investigate the applicability of them to this study. The correlations, except Kang [1], are well-known and frequently accepted in design and analysis. 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. 3. It is identified that the calculated heat transfer coefficients by Cornwell et al. [10] and Cooper [11] very much under predict the present experimental data. Rohsenow [12] and Kang's correlations [1] over-predict the present data. Although Kang's correlation is acceptable, it is necessary to reduce the range of the deviation in order to increase the accuracy of the correlation. Therefore, the introduction of a new geometric parameter is considered in this study.

Table 3. Summary of Published Correlations

Reference	Correlation
Kang [1]	$h_b = \left(0.7q'' + \dfrac{70.5 - 0.9q''}{32.1 + 0.01\phi}\right)\left(q''\dfrac{L}{D}\right)^{-0.21}$
Cornwell et al. [10]	$Nu_b = C_{tb}\,\mathrm{Re}_b^{2/3}$, $Nu_b = \dfrac{h_b D}{k_f}$, $\mathrm{Re}_b = \dfrac{q''}{h_{fg}}\dfrac{D}{\mu_f}$
Cooper [11]	$h_b = 55 p_R^{(0.12-0.2\log_{10}\varepsilon)}(-\log_{10} p_R)^{-0.55} M^{-0.5} q''^{0.67}$
Rohsenow [12]	$q'' = \mu_f h_{fg}\left[\dfrac{g(\rho_f - \rho_g)}{\sigma}\right]^{\frac{1}{2}}\left(\dfrac{C_{pf}\Delta T_{sat}}{h_{fg}\,\mathrm{Pr}_f^s\,C_{sf}}\right)^3$

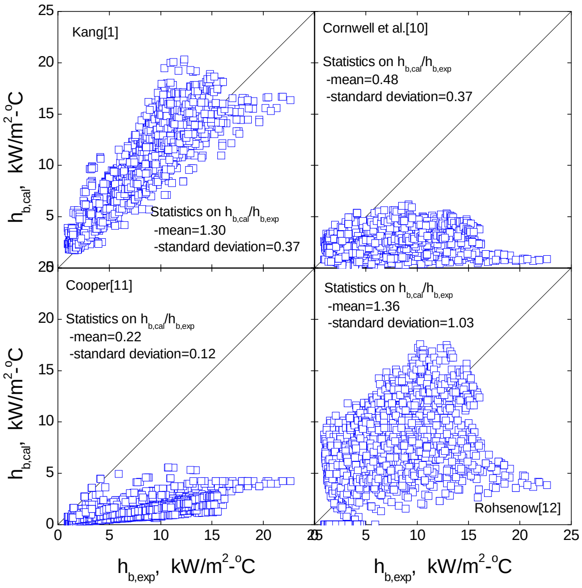

Fig. 3. Comparison of experimental data with published correlations.

To take into account effects of the surface roughness and the type of liquid a simple correlation is sought. 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:

$$h_b = C_\phi C_\varepsilon \,\mathrm{Re}^{0.01}\,\mathrm{Pr}^{-0.41} L_r^{-0.21} \tag{1}$$

$$C_\phi = 3.3q''^{0.79} + \frac{333.3 - 4.26q''}{(32.1 + 0.01\phi^2)q''^{0.21}}$$

$$C_\varepsilon = M^{-0.41} p_R^{-0.05(\log_{10}\varepsilon - 3)}$$

$$\mathrm{Re} = \frac{q''}{h_{fg}}\frac{D}{\mu_f}, \quad L_r = \frac{L}{D}$$

In the above equations, h_b and q'' are the heat transfer coefficient and the heat flux and the units are kW/m^2-°C and kW/m^2, respectively. The dimensions for ϕ and ε are ° (degree) and nm, respectively. Four dimensionless parameters (i.e., Re, Pr, p_R, and L_r) are introduced to incorporate the effects of liquids and the geometry. Re is Reynolds number and Pr is Prandtl number of the saturated liquid. p_R is reduced pressure. M is the molecular weight in kg/kmol, h_{fg} the enthalpy of vaporization in kJ/kg, μ_f liquid viscosity in Ns/m^2. The applicable ranges of the new correlation are L/D =5.25~42.52, q'' =7~160kW/m^2, ε =11.8~670nm, and ϕ =0°~90°.

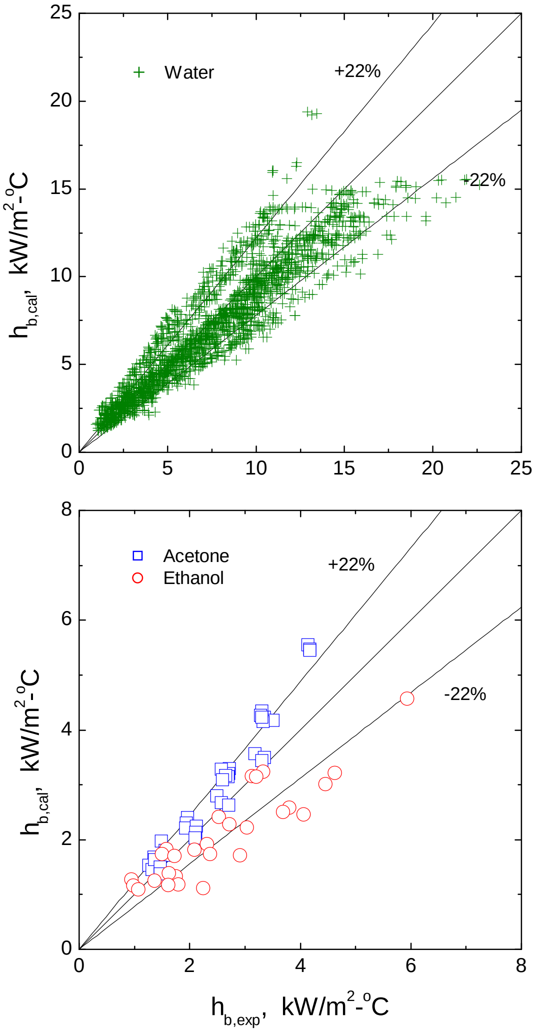

Fig. 4. Comparison of experimental data to calculated heat transfer coefficients by developed correlation.

A comparison between the heat transfer coefficients from the tests ($h_{b,\exp}$) and the calculated value ($h_{b,cal}$) by Eq. (1) is shown in Fig. 4. 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 1.00 and 0.22, respectively. The newly developed correlation predicts the present experimental data within ±22 %, with some exceptions. The scatter of the present data is of similar size to that found in other existing pool boiling data.

3. Conclusions

A new empirical correlation including surface roughness and dimensionless numbers was suggested to evaluate the pool boiling heat transfer coefficient of an inclined tube. Through the survey of published results, 2,105 data points for the tubes submerged in the saturated liquids at atmospheric pressure were obtained and the nonlinear least square method was used as a regression technique. The newly developed correlation well predicts the experimental data within ±22%, with some exceptions.

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