A New Correlation to Predict Nucleate Pool Boiling Heat Transfer in Vertical Annuli with Closed Bottoms

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1. Introduction

It is important to find a way of enhancing heat transfer coefficients if the space for heat exchanger installation is limited, as it is in advanced light water reactors [1]. One of the effective methods to increase heat transfer coefficients (h_b) of pool boiling is to consider a confined space [2]. It is well known from the literature that the confined boiling is an effective technique to enhance heat transfer [2-6].

Once the flow inlet at the tube bottom is closed, a very rapid increase in heat transfer coefficient is observed at low heat fluxes (q''). The similar tendency is observed regardless of the geometric shape. Yao and Chang [3] and Kang [6] investigated a vertical annulus while Rops et al. [5] investigated a confined plate. Fujita et al. [4], in other wise, used parallel plates with side and bottom inflow is restricted.

Around the upper region of the annulus with closed bottoms the downward liquid interrupts the upward movement of the bubble slugs. Thereafter, bubbles are coalescing into much bigger bubbles while fluctuating up and down in the annular space [6]. As the heat flux increases (1) the isolate bubble region, (2) the coalesced big size bubble region, and (3) the dryout region is observed in series [3]. The major causes of the heat transfer enhancement are related with the liquid film evaporation [3, 4] and active liquid agitation [6].

Literature review on the previous studies about crevice effects on pool boiling denotes that heat transfer is highly dependent on the geometric parameters. Therefore, it is necessary to quantify the effect of each geometric parameter to estimate heat transfer coefficients accurately.

Although some correlations [4, 7] were developed to predict pool boiling heat transfer in confined spaces based on open bottoms, the application of them to a confined space with closed bottoms could result in much error. To overcome the limits of the published correlations, Kang [8] developed a correlation to predict pool boiling heat transfer in annuli with closed bottoms. However, the outside tube length (L_o) of an annulus was not contained in the correlation. The length of the outer tube changes heat transfer [9, 10]. The heat transfer coefficients are enhanced or deteriorated due to the combination of the heated and outside tubes. Therefore, the inclusion of the outside tube into the correlation is considered in this study to improve Kang's previous correlation [8].

2. Methods and Results

A total of 494 data points has been obtained for heat flux versus wall superheat for various combinations of diameter, heated tube length, gap size, and the outside tube length of the vertical annulus with closed bottoms (Fig. 1). All data have been obtained from the combination of smooth stainless tubes and saturated water at atmospheric pressure. The range of the data set are D =19.1~25.4 mm, s =3.5~44.3 mm, L =0.20~0.57 m, L_o =0.2~0.6 m, and q'' =5~150 kW/m².

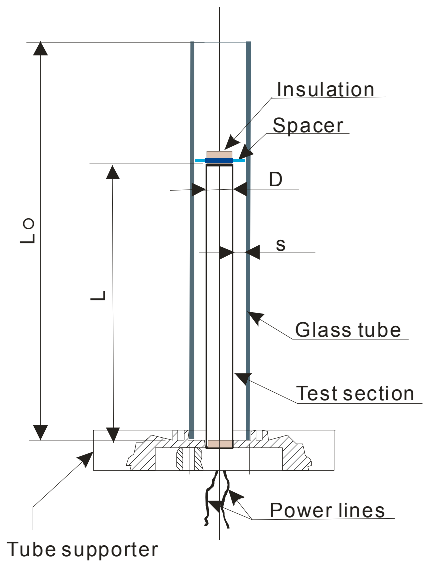

Fig. 1. Schematic diagram of the assembled annulus with closed bottoms.

According to Cornwell and Houston [11] and Chun and Kang [1], the heat transfer coefficients on a tube are closely related with the tube diameter. For a tube in a vertical orientation, the length of the tube should be included in the analyses to get more accurate heat transfer coefficients [12]. Recent study by Kang [9, 10] pointed out that the length of the outside tube of an annulus could change pool boiling heat transfer. Therefore, five dimensionless parameters containing D , L , L_o , s , and q'' were selected as independent variables to predict heat transfer coefficients. The important dimensionless parameters in boiling are

Nusselt number(Nu), Reynolds number(Re), and Bond number(Bo). In addition to the geometric parameter L_s , a new dimensionless parameter, $L_r = L_o / L$, is included for the analysis. As a result, an empirical correlation has been obtained using the experimental data and a computer program for statistical analyses (which uses the least square method as a regression technique). The suggested empirical correlation in dimensionless form is as follows:

$$Nu = 0.244 Re^{0.609} Bo^{1.622} L_s^{0.837} L_r^{0.197} \quad (1)$$

$$Nu = \frac{h_b}{k_f}\left[\frac{\sigma}{g(\rho_f - \rho_g)}\right]^{\frac{1}{2}}, \quad Bo = \frac{s}{\left[\frac{\sigma}{g(\rho_f - \rho_g)}\right]^{\frac{1}{2}}},$$

$$Re = \frac{q''}{h_{fg}\mu_f}\left[\frac{\sigma}{g(\rho_f - \rho_g)}\right]^{\frac{1}{2}}, \quad L_s = \frac{LD}{s^2}$$

To confirm the validity of the developed correlations, statistical analyses on the ratios of the predicted versus the experimental Nusselt numbers ($Nu_{predicted} / Nu_{experimental}$) have been performed. The mean and the standard deviation are 1.0249 and 0.1689, respectively. The developed correlation slightly over predicts the experimental data. But it is acceptable.

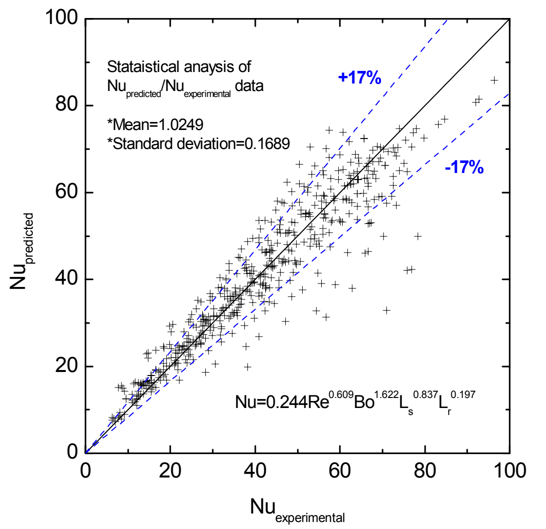

Fig. 2. Comparison of the predicted Nusselt numbers with the experimental values.

A comparison of the experimental Nusselt number with the one calculated by Eq. (1) is shown in Fig. 2. This figure indicates that the scatter of the present experimental data is within ±17%, with some exceptions, from the calculated values. The scatter of the present data is of similar size to that found in the other existing pool boiling data. As noted by Cornwell and Houston [11], 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. Although this model does contain inherent unidentified uncertain parameters, we continue the development of the correlation nevertheless. This is because the quantification of the experimental results may broaden its applicability to the thermal designs.

3. Conclusions

To investigate effects of geometric parameters on nucleate pool boiling heat transfer in a vertical annulus with closed bottoms an empirical correlation was developed. The proposed correlation, incorporating the ratio of tube lengths, predicts the experimental data of saturated water at atmospheric pressure with reasonable accuracy.

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