EFFECTS OF GEOMETRIC PARAMETERS ON NUCLEATE POOL BOILING OF SATURATED WATER IN VERTICAL ANNULI

MYEONG-GIE KANG
Department of Mechanical Engineering Education, Andong National University
388 Songchun-dong, Andong-city, Kyungbuk, 760-749, Korea
E-mail : mgkang@andong.ac.kr

Received May 13, 2008
Accepted for Publication September 1, 2008

Nucleate pool boiling of water in vertical annuli at atmospheric pressure has been studied experimentally and two empirical correlations have been suggested to obtain effects of geometric parameters on heat transfer. Data of the present and the previous tests range over a tube length of 0.50-0.57 m, a diameter of 16.5-34.0 mm, and an annular gap size of 3.7-44.3 mm. Through the analysis, tube bottom confinement (open or closed) has been investigated, as well. The developed correlations predict experimental data within a ±25% error bound. It has been identified that effects of the diameter and the length of heated tubes as well as the annular gap size should be counted into the analyses to estimate heat transfer coefficients accurately.

KEYWORDS : Pool Boiling, Annulus, Correlation, Bottom Confinement, Vertical Tube

1. INTRODUCTION

The mechanism of pool boiling heat transfer has been studied extensively in the past [1] since it is closely related with the thermal design of more efficient heat exchangers. Recently, it has been widely investigated in nuclear power plants for application to the design of new passive safety systems employed in advanced light water reactors [2,3]. To determine the required heat transfer surface area as well as to evaluate the system performance during postulated accidents, overall heat transfer coefficients applicable for passive heat exchangers are needed. Although many researchers have in the past two generations investigated effects of heater geometries on boiling heat transfer, knowledge of pool boiling heat transfer in a confined space is not enough; however, crevice effects on flow boiling have been widely studied [4-6].

One of the effective methods to increase heat transfer coefficients of pool boiling (h_b) is to consider a confined space around a heat exchanging tube. To find a way of enhancing the heat transfer coefficient is important if the space for heat exchanger installation is limited, as it is in advanced light water reactors [1]. Studies of the crevices can be divided into two categories. One of these is about annuli [3,7,8] (see Table 1) and the other one is about plates [9-11]. In addition to the geometric conditions, flow to the crevices can be regulated. Some geometry has a closed bottom [3,7,10,12].

It is well known from the literature that confined boiling is an effective technique to enhance heat transfer. It can result in heat transfer improvements of up to 300%-800% at low heat fluxes (q''), as compared with unconfined boiling [7,9]. The boiling heat transfer coefficient usually increases when the gap size decreases at low heat fluxes. Recent research [3,13] on the annulus shows that some discrepancies exist among the results for the same gap size when the other geometric parameters are different from each other. Kang's data [3] is different from Kang and Han's data [13] whereas both data have the same gap sizes (s=3.90 or 15.00 mm) and tube diameter (D=25.4 mm). The measured heat transfer coefficients in Kang's data are more than 30% higher compared to Kang and Han's data at heat fluxes higher than 30 kW/m^2. The difference in tube length can be counted as one of the possible causes of the discrepancy. As Kang [14] already investigated, incorporating effects of the tube length into the pool boiling analysis is important when the heated tube is in a vertical orientation.

Improved heat transfer characteristics with this restriction might be attributed to an increase in the heat transfer coefficient due to vaporization from the thin liquid film on the heating surface or to increased bubble

Table 1. Summary of Previous Works about Annular Gap Effects on Pool Boiling Heat Transfer

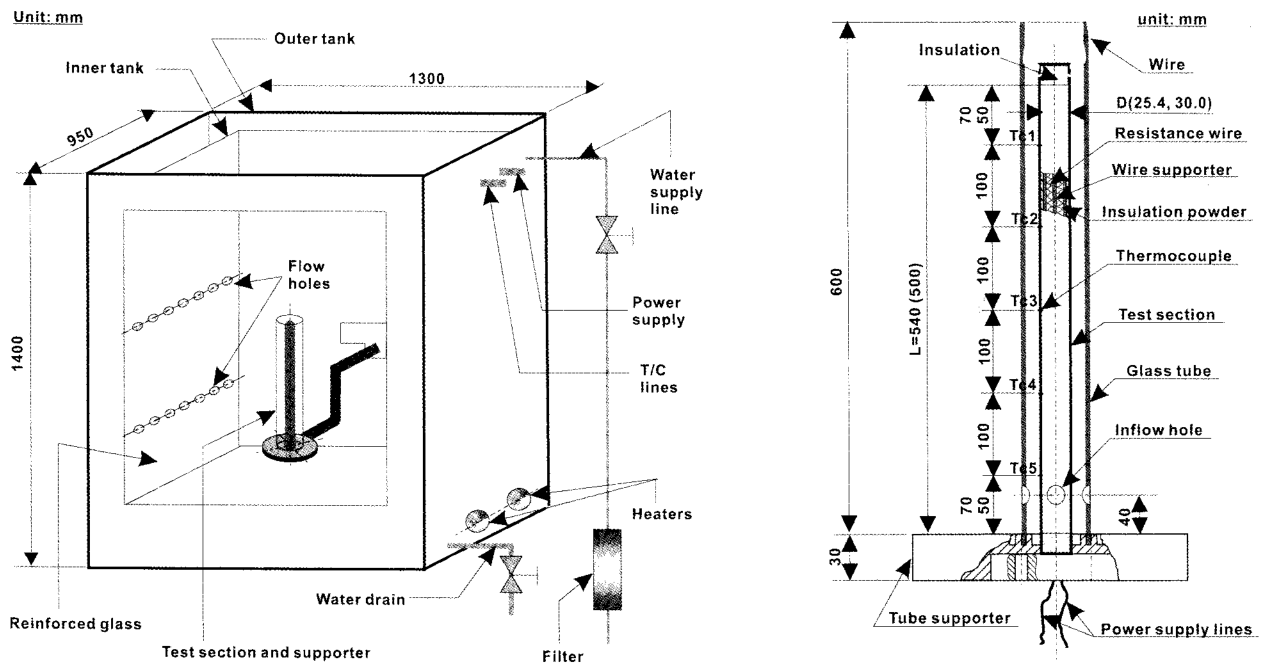
Author	Remarks
Yao and Chang (1983)	- heater: stainless steel tube (D =25.4mm, L =25.4 and 76.2mm) - liquid: R-113, acetone, and water at 1 atm - liquid condition: saturated - geometry: vertical annuli with closed bottoms - gap sizes: 0.32, 0.80, and 2.58mm
Hung and Yao (1985)	- heater: stainless steel tube (D =25.4mm, L =101.6mm) - liquid: R-113, acetone, and water at 1 atm - liquid condition: subcooled or saturated - geometry: horizontal annuli - gap sizes: 0.32, 0.80, and 2.58mm
Kang (2001)	- heater: stainless steel tube (D =25.4mm, L =570mm) - liquid: water at 1 atm - liquid condition: saturated - geometry: vertical annuli with open or closed bottoms - gap sizes: 3.9 and 15mm
Kang and Han (2002)	- heater: stainless steel tube (D =25.4mm, L =500mm) - liquid: water at 1 atm - liquid condition: saturated - geometry: vertical annuli with open or closed bottoms - gap sizes: 3.9, 15, 25.1, 34.9, and 44.3mm

activity [8,9]. In confined spaces, at a fixed heat flux, the mass of vapor generated is constant, so that with decreasing gap size, higher vapor velocities are induced. With the increased vapor velocities, the shear stress on the liquid film at the heated surface increases and the liquid film is reduced in thickness. Since the major heat transfer resistance is the heat conduction across the liquid film, the reduced film thickness increases the heat transfer coefficient [8]. According to Cornwell and Houston, the bubbles sliding on the heated surface agitate environmental liquid [15]. In a confined space a kind of pulsating flow due to the bubbles is created and as a result very active liquid agitation is generated [3]. The increase in the intensity of the liquid agitation increases heat transfer.

Summarizing the previous works about crevice effects on pool boiling heat transfer it can be said that the heat transfer coefficient is highly dependent on not only the gap size but also on the other geometric parameters and the confinement condition. Therefore, it is necessary to quantify the effect of each geometric parameter to estimate heat transfer coefficients accurately. Although many correlations were developed for flow boiling in annuli [4,5] or pool boiling on unrestricted tubes or plates [1], to this author's knowledge no general correlation has been suggested for pool boiling in annuli. Therefore, the development of new correlations containing geometric parameters is selected as the major objective of the present study to estimate heat transfer coefficients of pool boiling in vertical annuli with open or closed bottoms.

2. EXPERIMENTS

A schematic view of the present experimental apparatus and test sections is shown in Fig. 1. The water tank (Fig. 1(a)) is made of stainless steel and has a rectangular cross section (950 × 1300 mm) and a height of 1400 mm. The measurements of the inner tank are 800 × 1000 × 1100 mm (depth × width × height). The inside tank has several flow holes (28 mm in diameter) to allow fluid inflow from the outer tank. Four auxiliary heaters (5 kW/heater) are installed at the space between the inside and the outside tank bottoms. The heat exchanger tubes are simulated by resistance heaters (Fig. 1(b)) made of a very smooth stainless steel tube. The surface of the tube is finished through a buffing process to have smooth surface. Electric



(a) water tank

(b) assembled test section

Fig. 1. Schematic Diagram of the Experimental Apparatus

power of 220 V AC is supplied through the bottom side of the tube.

The outside of the tube is instrumented with five T-type sheathed thermocouples (diameter is 1.5 mm). The thermocouple tip (about 10 mm) is brazed on the tube wall. The water temperatures are measured with six sheathed T-type thermocouples brazed on a stainless steel tube that is placed vertically at a corner of the inside tank. All thermocouples are calibrated at a saturation value (100 °C since all tests are done at atmospheric pressure). To measure and/or control the supplied voltage and current, two power supply systems (each having three channels for reading of both voltage and current in digital values) are used. The capacity of each channel is 10 kW.

For the tests, the heat exchanging tube is assembled vertically at the supporter (Fig. 1(a)) and an auxiliary tube supporter (Fig. 1(b)) is used to fix a glass tube (Fig. 1(b)). To create the annular condition, several glass tubes of different inside diameters are used (see Table 2). A fixture made of slim wires is inserted into the upper side of the gap to maintain the space between the heating tube and the glass tube.

After the water tank is filled with water until the initial water level is reached at 1100 mm, the water is then heated using four pre-heaters at constant power. When the water temperature reaches a saturation value (i.e., T_{sat}=100 °C since all the tests are run at atmospheric pressure condition), the water is then boiled for 30 minutes to remove the dissolved air. The temperatures of the tube surfaces (T_W) are measured when they are at steady state while controlling the heat flux on the tube surface with input power.

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

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

where V and I are the supplied voltage (in volts) and current (in amperes), 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 of values of the temperatures measured by thermocouples.

The error bounds of the voltage and current meters used for the test are ±0.5% of the measured value. Therefore, the calculated power (voltage current) has ±1.0% error bound. Since the heat flux has the same error bound as the power, the uncertainty in the heat flux is estimated to be ±1.0%. When evaluating the uncertainty of the heat flux, the error of the heat transfer area is not counted because the uncertainties of the tube diameter and the tube length are ±0.1 mm and its effect on the area is negligible.

The measured temperature has uncertainties originating from the thermocouple probe itself and translation of the

Table 2. Experimental Data for Correlation Development

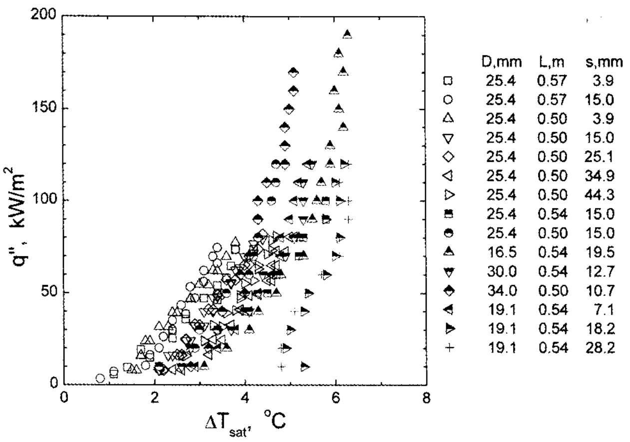
Reference	D, mm	L, m	s, mm	Bo	Number of data points	
					Open bottoms	Closed bottoms
[3]	25.4	0.57	3.9	1.56	16	16
	25.4	0.57	15.0	5.99	18	21
[13]	25.4	0.50	3.9	1.56	20	20
	25.4	0.50	15.0	5.99	20	20
	25.4	0.50	25.1	10.02	20	20
	25.4	0.50	34.9	13.93	20	20
	25.4	0.50	44.3	17.68	20	20
[16]	16.5	0.54	19.5	7.78	19	19
[17]	19.1	0.54	7.1	2.81	12	12
	19.1	0.54	18.2	7.24	12	12
	19.1	0.54	28.2	11.25	12	12
[12]	19.1	0.54	3.7	1.46	-	11
	19.1	0.54	6.4	2.53	-	12
	19.1	0.54	18.0	7.16	-	12
[18]	34.0	0.50	10.7	5.99	17	17
Present	25.4	0.54	15.0	5.99	10	10
	25.4	0.50	15.0	5.07	12	12
	30.0	0.54	12.7	4.27	12	-
		Total			240	266

measured electric signals to digital values. To evaluate the error bound of a thermocouple probe, three thermocouples brazed on the tube surface were submerged in an isothermal bath containing water. The measured temperatures were compared with the set temperature (80 °C) of the isothermal bath of ±0.01 °C accuracy. Since the duration to finish a set of the present test took less than one hour, the elapsed time to estimate the uncertainty of the thermocouple probes was set as one hour. According to the results, the deviation of the measured values from the set value is within ±0.1 °C, including the accuracy of the isothermal bath. To estimate the total uncertainty of the measured temperatures the translation error of the data acquisition system must be included. The error bound of the system is ±0.05 °C. Therefore, the total uncertainty of the measured temperatures is defined by adding the above errors; the uncertainty value is ±0.15 °C. The uncertainty in the heat transfer coefficient can be determined through the calculation of $q''/\Delta T_{sat}$ and is within ±6%.

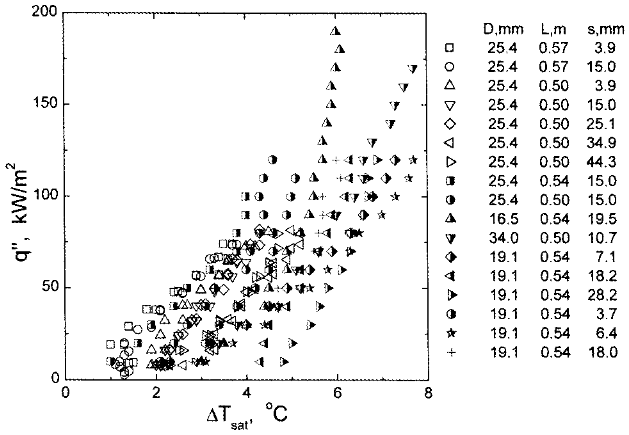
3. RESULTS AND DISCUSSION

As summarized in Table 2, a total of 506 data (240 with open bottoms and 266 with closed bottoms) has been obtained for heat flux versus wall superheat for various combinations of diameter, tube length, gap size, Bond number (Bo), and bottom conditions. All tests listed in Table 2 have been performed at atmospheric pressure. Yao and Chang's data [7] are not shown for the correlation development since the length of their heated tube is much shorter than that of the tube measured in the present data.

Figure 2 is plots of the heat flux versus wall superheat data for the annuli with different bottom conditions. The heat transfer coefficients can be calculated by dividing the heat flux by the wall superheat as defined in Eq. (1). The increase in heat flux usually results in the increase in wall superheat. Some exceptions are found when the heat fluxes less than 20kW/m^2 and the bottom flow inlet is closed. In such a case, the wall superheat slightly decreases as the heat flux increases. This is due to the pulsating flow in the annular space [3]. The increase in the gap size usually increases the wall superheat. However, this tendency depends on the bottom flow-inlet condition and the gap size. For the annuli with open bottoms, the increase in the gap size increases the wall superheat as the gap size gets to a threshold value. After this point, the increase in the gap size has no significant effect on the wall superheat.



(a) annul with open bottom



(b) annul with closed bottom

Fig. 2. Plots of q'' Versus ΔT_{sat} Data

For the annuli with closed bottoms, the increase in the gap size increases the wall superheat until the gap size gets to the threshold value. Then, the increase in the gap size decreases the wall superheat. From the results, the convective term for the open bottoms and the bubble coalescence for the closed bottoms can be suggested as the major heat transfer mechanisms when the gap size varies. The change in the tube length also varies heat transfer. Summarizing the effect of a certain thermo-geometric parameter on heat transfer, there does exist a tendency. But, the tendency is highly dependent on the other parameters. The data for the closed bottoms show a more complicated tendency and broader wall superheat comparing to the open bottoms. This suggests the existence of more complex heat transfer mechanisms in the annuli with closed bottoms.

It is not realistic to obtain any general theoretical correlation for heat transfer coefficients in nucleate boiling. This is because the boiling occurs at nucleation sites, and the number of sites is very dependent on (a) the physical condition and preparation of the surface; and (b) how well the liquid wets the surface and how efficiently the liquid displaces air from the cavities [19]. Moreover, geometric conditions make the situation more complicated. 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.

According to Cornwell and Houston [15] and Chun and Kang [1], heat transfer coefficients on a tube are closely related with the tube diameter. For tubes in vertical orientation, the length of a tube should be included in the analyses to get more accurate heat transfer coefficients [14]. Therefore, four dimensionless parameters containing D, L, s, and q'' are selected as independent variables to predict boiling heat transfer coefficients. The important dimensionless parameters in boiling are Nusselt number (Nu), Reynolds number (Re), and Bond number [7,20,21]. A geometric dimensionless parameter (L_r) is also included as follows:

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

$$\mathrm{Re} = \frac{q''}{i_{fg}\mu_f}\left[\frac{\sigma}{g(\rho_f - \rho_g)}\right]^{\frac{1}{2}} \tag{3}$$

$$Bo = \frac{s}{\left[\frac{\sigma}{g(\rho_f - \rho_g)}\right]^{\frac{1}{2}}} \tag{4}$$

$$L_r = \frac{LD}{s^2} \tag{5}$$

In the above equations k_f, μ_f, and σ represent thermal conductivity, viscosity, and surface tension of liquid, respectively. ρ_f is liquid density and ρ_g is vapor density. i_{fg} indicates latent heat of vaporization and g is acceleration due to gravity.

As a result, two empirical correlations, one for open bottoms and the other for closed bottoms, have been obtained using previous and present experimental data and a computer program for statistical analyses (which uses the least square method as a regression technique). The suggested empirical correlations in dimensionless form are as follows:

$$Nu = 20.9\,\mathrm{Re}^{0.62}\,Bo^{0.43}\,L_r^{0.27} \quad \text{(For open bottoms)} \tag{6}$$

$$Nu = 14.4\,\mathrm{Re}^{0.49}\,Bo^{0.50}\,L_r^{0.28} \quad \text{(For closed bottoms)} \tag{7}$$

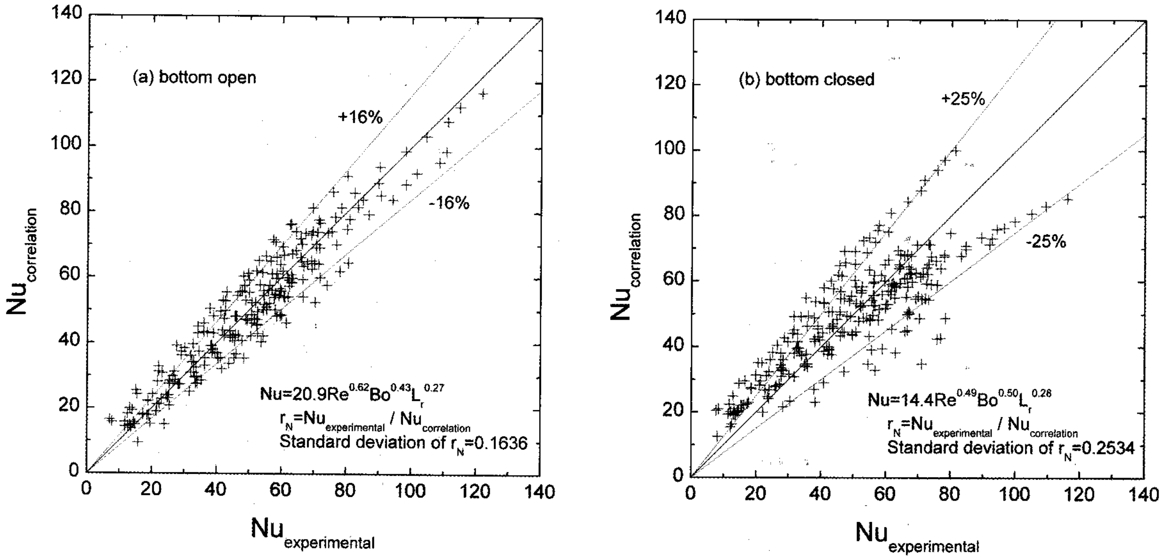


Fig. 3. Comparison of Experimental Data to Calculated Values

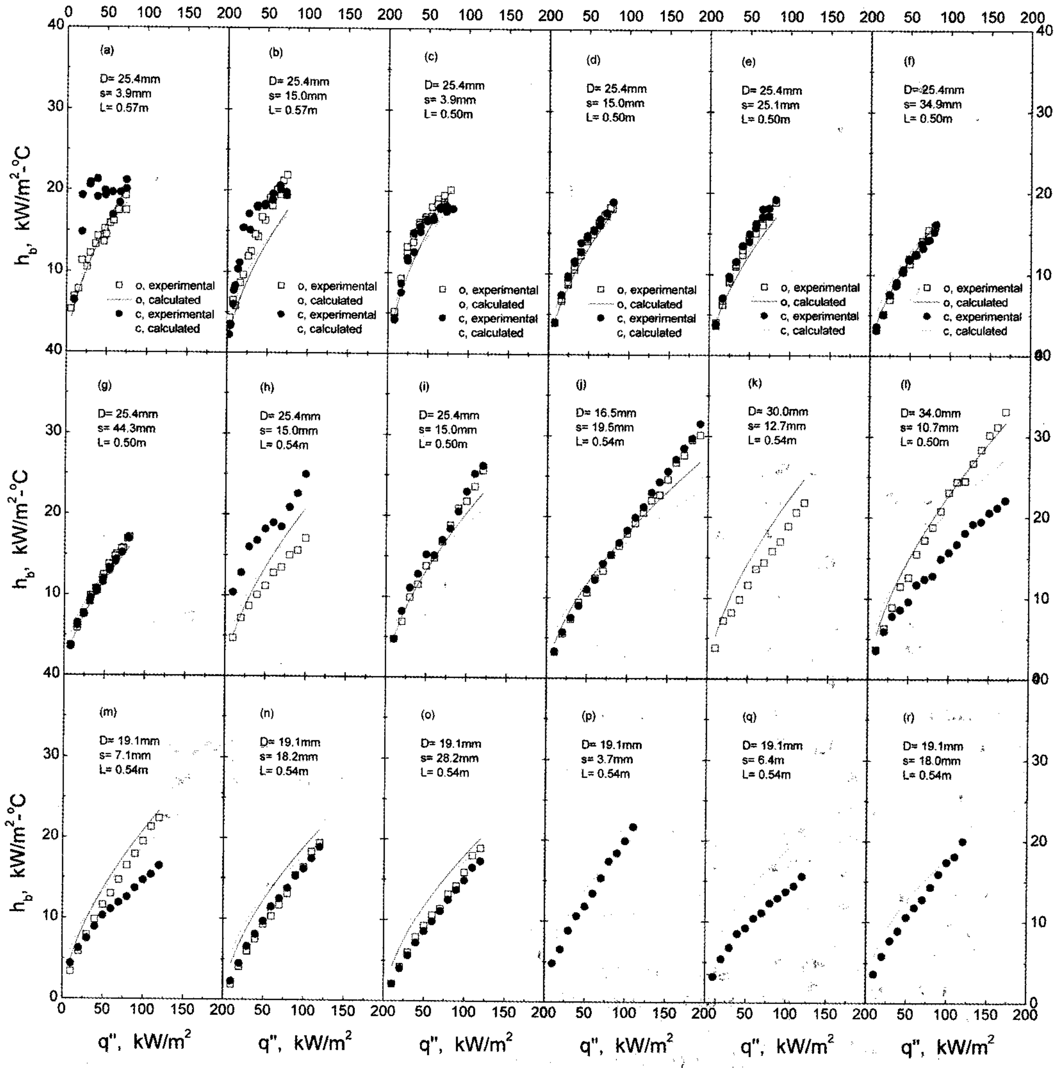


Fig. 4. Comparison of Experimental and Calculated Data (o : Open Bottom, c : Closed Bottom)

According to the equations, the major parameter affecting heat transfer is somewhat different between groups. The governing parameter is Reynolds number when the annulus has open bottoms whereas the governing parameter is Bond number when the annulus has closed bottoms. Effects of the geometric parameter, L_r, on heat transfer are almost the same regardless of the bottom confinement condition. To confirm the validity of the developed correlations, statistical analyses on the ratios of the experimental versus the correlated Nusselt numbers (i.e., $Nu_{\text{experiment al}}/Nu_{\text{correlation}}$) have been performed. The standard deviations for the annuli with open bottoms and the closed bottoms are 0.1635 and 0.2534, respectively. The developed correlations are varied for the parameter values of D=16.5~34.0mm, s=3.7~44.3mm, L=0.50~0.57m, and q''=5~190kW/m^2.

A comparison of the experimental Nusselt number with the one calculated by Eq. (6) and (7) is shown in Fig. 3. This figure indicates that the scatter of the present experimental data is within ±16 % (bottom open) and ±25 % (bottom closed), 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 [15], 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.

In Fig. 4, the measured heat transfer coefficient is plotted against the heat flux along with the fitted curve of Eq. (6) and (7). Both data of open and of closed bottoms are compared with each other. The developed correlation predicts the data of annuli with open bottoms very well. However, some discrepancy is observed in the closed bottom case. As Kang [3] already explained, once the bottom side is closed, very strong liquid agitation and, accordingly, sudden decrease in tube wall superheat is observed at lower heat fluxes. In other words, sudden deterioration in heat transfer is observed at higher heat flux due to coalesced bubble slugs. This makes it difficult to predict the heat transfer coefficient as a simple equation form like Eq. (7). However, the correlation predicts the general tendency in an acceptable error bound and the discrepancy between the experimental data and the calculated values is not so significant.

4. CONCLUSIONS

An experimental parametric study on vertical annuli has been carried out under nucleate pool boiling conditions. The main conclusions of the present experimental results are as follows:

(1) It has been identified that the major dimensionless parameter for heat transfer is the bottom confinement condition. Reynolds number is the governing parameter for the annuli with open bottoms whereas Bond number is the governing parameter for annuli with closed bottoms.

(2) Two empirical correlations to predict heat transfer coefficients, one for the open and the other for the closed, have been obtained in terms of Nusselt number, Reynolds number, Bond number and the dimensionless geometric parameter. The overall scattering ranges of the present data are within ±16 % (bottom open) and ±25 % (bottom closed) from the fitted curves of the developed empirical correlations.

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