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Effects of water subcooling on heat transfer in vertical annuli

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Abstract

To obtain effects of major geometric parameters on subcooled heat transfer in vertical annuli three gap sizes (7.05, 18.15, and 28.2 mm) and two bottom conditions (open or closed) have been investigated experimentally in water at atmospheric pressure. Up to 50 °C of liquid subcooling has been tested and 429 data points were obtained at both single phase and boiling regions. The increase in pool subcooling results in much change in heat transfer coefficients. The governing mechanisms are suggested as single-phase natural convection and liquid agitation for the annuli with open bottoms while liquid agitation and bubble coalescence are the major factors at the bottom-closed annuli. Four empirical correlations for the heat transfer coefficient have been suggested in terms of the gap size, the degree of subcooling, and the heat flux. The correlations predict the heat transfer data of single phase and of boiling within ±5% and ±20%, respectively.

1. Introduction

Pool boiling heat transfer has been studied over a long period of time and recently has been the subject of widespread investigation in nuclear power plants for application to advanced light water reactors [1]. Many passive heat exchangers that transfer decay heat to a water tank by pool boiling have been adopted in advanced nuclear reactors in order to meet inherent safety goals. These passive safety systems maintain the coolant temperature under a required value within a fixed time. Among the design parameters, two important subjects are (1) identification of effects of subcooling on pool boiling heat transfer and (2) determination of a means of increasing heat transfer.

Bradfield [2] published some experimental results on subcooled boiling in the transition region. Judd et al. [3] investigated effects of subcooling on boiling heat transfer in the nucleate boiling region. They theoretically studied the relation between the degree of subcooling and superheating through analyses of previous experimental results. Some experimental results have recently been published that identify the relation between subcooling and boiling heat transfer with consideration of the heating surface as a wire [4–6]. Kang [7] published some preliminary studies of a tube to investigate effects of subcooling on pool boiling heat transfer and thermal mixing by using a vertically installed stainless steel tube of 19.1 mm diameter and water. Effects of subcooling on boiling heat transfer have been extensively studied in terms of regarding a fluid in forced circulation and/or heating geometry in the form of a wire. However, there has been very little reported study on subcooled pool boiling on a tube. Since mechanisms of forced convective boiling are different from pool boiling [1], they should be treated separately. Moreover, results of wires cannot be applied to tubes without significant modification, since there are many differences in heat transfer between tubes and wires [8].

Although many researchers have investigated effects of heater geometries on boiling heat transfer, knowledge on narrow spaces and pool boiling heat transfer is still very limited. However, gap effects in flow boiling have been widely studied [9–11]. Studies on crevices can be divided into two categories, annuli [12–15] and plates [16–18]. Some previous results related to crevice effects on pool boiling heat transfer in an annulus are summarized in Table 1. In addition to the geometric conditions, flow to the crevices can be limited. Some geometry may have the form of confined conditions

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Nomenclature

A	heat transfer area	t	time
D	heating tube diameter	T_b	bulk temperature in the annulus
h_b	heat transfer coefficient	T_{sat}	saturation temperature
I	supplied current	T_W	tube wall temperature
L	heated tube length	T_{wat}	liquid temperature
q	input power	V	supplied voltage
q''	heat flux	ΔT_{sat}	tube wall superheating ($=T_W - T_{sat}$)
s	gap size	ΔT_{sub}	liquid subcooling ($=T_{sat} - T_{wat}$)

Table 1
Summary of previous works about annular gap effects on pool boiling heat transfer

Author	Remarks
Yao and Chang [12]	• Heater: stainless steel tube ($D = 25.4$ mm, $L = 25.4$ and 76.2 mm) • 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 2.58 mm
Hung and Yao [13]	• Heater: stainless steel tube ($D = 25.4$ mm, $L = 101.6$ mm) • Liquid: R-113, acetone, and water at 1 atm • Liquid condition: subcooled or saturated • Geometry: horizontal annuli • Gap sizes: 0.32, 0.80, and 2.58 mm
Kang and Han [14]	• Heater: stainless steel tube ($D = 25.4$ mm, $L = 500$ mm) • 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 44.3 mm
Kang [15]	• Heater: stainless steel tube ($D = 19.1$ mm, $L = 540$ mm) • Liquid: water at 1 atm • Liquid condition: subcooled and saturated • Geometry: vertical annulus with closed bottoms • Gap sizes: 7.05 mm

to restrict fluid inflow [12,14–16]. However, results dealing with effects of subcooling in a vertical annulus are not many. As shown in Table 1, only Kang [15] studied effects of subcooling in a vertical annulus with closed bottoms of 7.05 mm gap size (s). Although, Hung and Yao obtained subcooling effects on pool boiling heat transfer in an annulus, the orientation of the annulus was horizontal. Since there is much difference in heat transfer due to the orientation of the heater [19], results of a horizontal annulus cannot be applied to a vertical annulus.

Summarizing the previous results, effects of subcooling on boiling heat transfer have been studied much as the fluid is in forced circulation and/or the heated geometry is not confined in a narrow space. Up to the author's knowledge, no previous results concerning about subcooled pool boiling in vertical annuli have been published except Kang [15]. However, Kang [15] only studied the annulus of 7.05 mm gap for the closed bottom condition. To identify effects of liquid subcooling on heat transfer in vertical annuli, more annular gap values and additional confinement should be studied. Therefore, the present study is aimed at the investigation of subcooled pool boiling in vertical annuli with open or closed bottoms by considering additional annular gaps.

2. Experiment

A schematic view of the present experimental apparatus and test sections is shown in Fig. 1. The water storage tank (Fig. 1(a)) is made of stainless steel and has a rectangular cross-section (950×1300 mm) and a height of 1400 mm. This tank has a glass view port (1000×1000 mm), which permits viewing and photographing of the tubes. The tank has a double container system. The size of the inner tank is $800 \times 1000 \times 1100$ mm (depth $\times$ width $\times$ height). The bottom side of the inner tank is situated 200 mm above the bottom of the outer tank. The inside tank has several flow holes (28 mm in diameter) to allow fluid inflow from the outer tank. To diminish the effects of inflow from the outside tank, holes are situated 300 and 800 mm high from the bottom of the inside tank. Four auxiliary heaters (5 kW/heater) were installed at the space between the inside and the outside tank bottoms to boil the water and to maintain the required conditions. To reduce heat loss to the environment, the left, right, and rear sides of the tank were insulated by glass wool of 50 mm thickness. The heat exchanger tubes are simulated by a resistance heater (Fig. 1(b)) made of a very smooth stainless steel tube ($L = 540$ mm and $D = 19.1$ mm). The surface of the tube was finished through a buffing process so as to have a smooth surface. Electric power was supplied through the bottom side of the tube. For the test, 220 V AC was used. Fig. 1(c) and (d) shows a glass tube and its supporter and the assembled test section, respectively.

The tube outside was instrumented with five T-type sheathed thermocouples (diameter is 1.5 mm). The thermocouple tip (about 10 mm) was bent at a 90-degree angle and the bent tip was brazed on the tube wall. The locations of

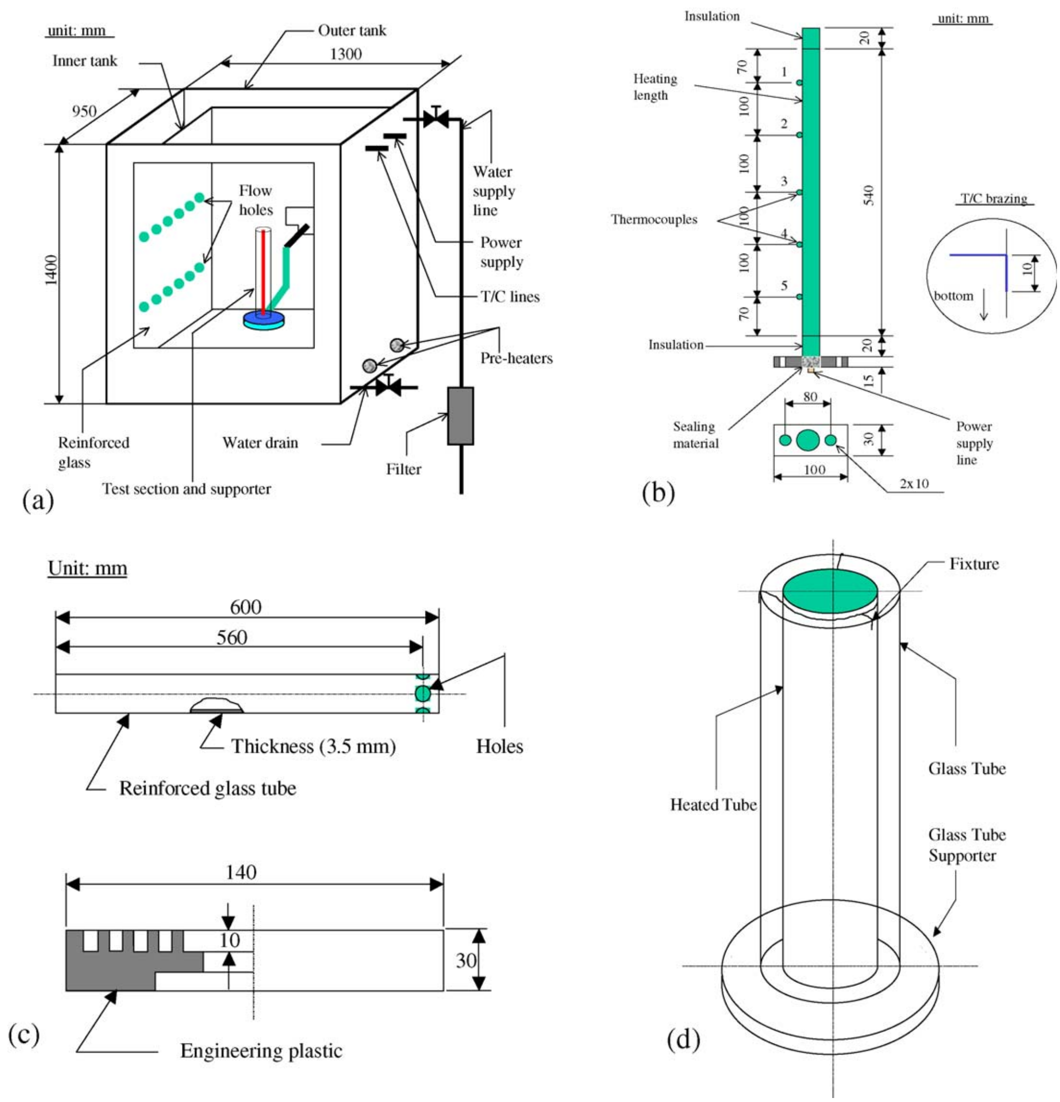

Fig. 1. Schematic diagram of experimental apparatus.

the thermocouples are 70, 170, 270, 370, and 470 mm from the heated tube bottom, as shown in Fig. 1(b). The water temperatures were measured with six sheathed T-type thermocouples placed vertically at a corner of the inside tank. To measure bulk temperatures in the annuli, five T-type thermocouples were inserted in the mid-space between the inside and the outside tubes. The locations of the thermocouples are same to the thermocouples brazed on the tube surface. All thermocouples were calibrated at a saturation value. To measure and/or control the supplied voltage and current, two power supply systems (each having three channels for reading both voltage and current in digital values) were used. The capacity of each channel is 10 kW.

For the tests, the heat exchanger tubes are placed vertically at the supporter and a glass tube supporter is used to fix a glass tube. To make annular conditions, three glass tubes (see Table 2) with six flow holes were used. The side with holes is placed at the tank bottom to make the annuli open. In other words, the side without holes is placed at the tank bottom for the closed bottom tests. A fixture made of slim wires was inserted into the upper side of the gap to maintain the space between the heating tube and the glass tube.

Table 2
Test matrix and q'' versus ΔT data

Bottom condition	Gap, s (mm)	Heat flux, q'' (kW/m^2)	Subcooling, ΔT_{sub} (°C)	Number of data	
				Single	Boiling
No restriction	∞	0–120	0–50	36	24
Open	7.05	0–120	0–50	36	33
Open	18.15	0–120	0–50	38	34
Open	28.2	0–120	0–50	37	35
Closed	7.05	0–120	0–50	1	71
Closed	18.15	0–120	0–50	9	63
Closed	28.2	0–120	0–50	20	52

Single phase data in annuli = 141 points (open/closed = 111/30).
Boiling data in annuli = 288 point (open/closed = 102/186).

After the water storage tank was adjusted until the initial water level was 1100 mm from the outer tank bottom, the water was heated using four pre-heaters at constant power (5 kW/heater). Through the heating process, temperatures of the water were measured. When the water temperature (T_{wat}) reached the required value, power to the pre-heaters was turned off and electricity was supplied to the heated tube. The temperatures of the water and tube surfaces were measured while controlling heat fluxes. In this manner a series of experiments was performed for various liquid subcooling.

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

$$q'' = \frac{q}{A} = \frac{VI}{\pi DL} = h_{\mathrm{b}}\Delta T, \tag{1}$$
$$\Delta T = T_{\mathrm{W}} - T_{\mathrm{wat}}: \text{ single tube,}$$
$$\Delta T = T_{\mathrm{W}} - T_{\mathrm{b}}: \text{ annuli,}$$

where V and I are the supplied voltage (in volt) and current (in ampere), and D and L are the outside diameter and the length of the heated tube, respectively. T_{W} and T_{b} represent the measured temperatures of the tube surface and water in the annulus, respectively. T_{W} and T_{b} used in Eq. (1) are the arithmetic average values of the temperatures measured by thermocouples. To determine local values of T_{W} and T_{b}, the measured temperatures were time-averaged for 90 s.

The error bounds of the voltage and current meters used for the test were ±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 taken into account since 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 originated from the thermocouple probe itself, thermocouple brazing, and translation of the measured electric signals to digital values. To evaluate the error bound of the 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 an isothermal bath of ±0.01 °C accuracy. Since the time to complete one set of the present test was less than 1 h, the elapsed time to estimate the uncertainty of the thermocouple probes was set as 1 h. 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. Since the thermocouples were brazed on the tube surface, the conduction error through the brazing metal must be evaluated. The brazing metal is a type of brass and the averaged brazing thickness is less than 0.1 mm. The maximum temperature decrease due to this brazing is estimated as 0.15 °C. 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, giving a value of ±0.3 °C. The uncertainty in the heat transfer coefficient can be determined through the calculation of $q''/\Delta T$ and is within ±10%.

Fig. 2 shows local and average temperatures of water in the tank. Fig. 2(a) shows temperature distribution along the tank height as time elapses at $q'' = 110\ \mathrm{kW/m^2}$. The prerequisite condition to evaluate effects of liquid subcooling on pool boiling heat transfer is uniform temperature distribution. To prevent thermal stratification [7] along the tank height without utilizing a stirrer a double container type tank was adopted. As shown in the figure, no

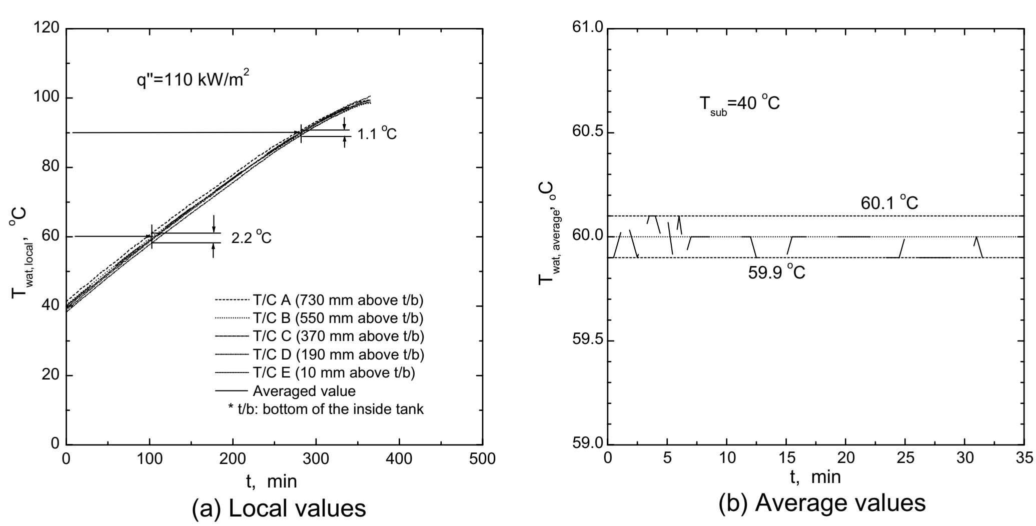

Fig. 2. Changes in water temperatures in tank as time elapses.

significant temperature difference exists between the uppermost (T/C A) and the lowermost (T/C E) thermocouple readings. At $T_{wat} = 60$ °C the difference between two local values is 2.2 °C. The upper region of the water becomes warm more rapidly than the lower regions due to bubbles coming from the lower side. As the degree of subcooling is higher, flow circulation is very limited around the upper region. Therefore, the largest difference between two temperatures is observed at higher subcooling. The difference decreases gradually as the water becomes saturated. Moreover, there is no horizontal temperature gradient in the tank except the annular space. Fig. 2(b) shows changes in the average water temperature during the test of $\Delta T_{sub} = 40$ °C. For the period, the temperature fluctuates within ±0.1 °C, which can thus be neglected.

Fig. 3 shows changes of bulk temperatures in the annuli as the heat flux and subcooling change. For the annuli with open bottoms T_b is slightly higher than the water temperature (T_{wat}) in the tank. The difference between the temperatures increases as the gap size decreases or the heat flux increases. As $s = 7.05$ mm and $q'' = 120$ kW/m^2, the difference between $T_b - T_{wat}$ is 5.5 °C at $\Delta T_{sub} = 50$ °C. The increase in the degree of subcooling (ΔT_{sub}) also increases the difference between two temperatures. As $\Delta T_{sub} \leqslant 20$ °C only small difference (less than 3 °C) is observed between the temperatures regardless of the gap size and the heat flux. For the annuli with closed bottoms, much difference is observed between the bulk and the water temperatures. As $s = 7.05$ mm and $q'' = 120$ kW/m^2, the difference between $T_b - T_{wat}$ is 33.1 °C at $\Delta T_{sub} = 50$ °C. The decrease in the gap size increases the difference between the temperatures. However, the increase in the heat flux results in somewhat different trend comparing to the annuli with open bottoms as the gap size decreases. For $s = 7.05$ mm and $\Delta T_{sub} \geqslant 20$ °C the difference between the bulk and the water temperatures becomes decreasing as the heat flux increases. As $\Delta T_{sub} = 10$ °C the temperature in the annuli becomes almost the saturation point. The difference between the bulk and the water temperatures is mainly because of the difference in the intensity of liquid agitation. The intensity gets larger in the annuli due to the narrower flow space. For the annuli with closed bottoms the intensity is magnified because the pulsating flow is generated in the gap space [14,15]. However, at $s = 7.05$ mm the inflow to the space is disturbed at the closed bottoms and this would be the cause of the decrease in the temperature difference at higher heat fluxes.

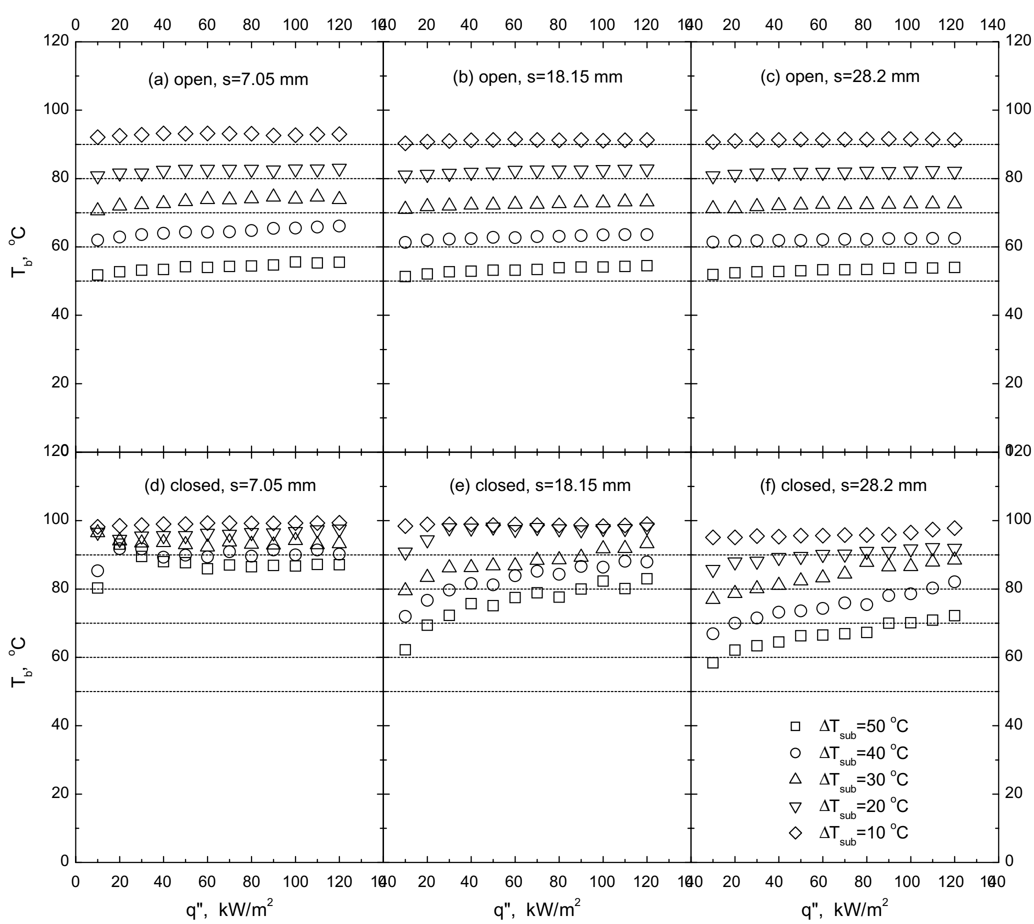

Fig. 3. Changes in bulk temperatures in annuli.

3. Correlations of experimental data

As summarized in Table 2, a total of 429 data (213 with open bottoms and 216 with closed bottoms) has been obtained for the heat flux versus the wall superheating for various combinations of the annular gap and liquid subcooling. No boiling can occur whilst the temperature of the heating surface remains below the saturation temperature of the fluid at that particular location. The minimum limiting condition for nucleation is given by $T_{\text{sat}} \leqslant T_{\text{W}}$ [20]. The data having positive wall superheat are assumed to be in the boiling regions. Fig. 4 is results of the data plotting and shows the regions of single phase and boiling heat transfer as functions of the heat flux and the liquid subcooling. 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 upon (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 [21]. To take account of effects of the gap size, the heat flux, and liquid subcooling simple correlations are sought and, as a result, four empirical correlations (two for single phase heat transfer and the others for boiling heat transfer) have been obtained using present experimental data and the statistical analysis computer program (which uses the least square method as a regression technique) as follows: At single phase regions:

$$h_{\text{b}} = 0.458q''^{0.895}/s^{0.088}\Delta T_{\text{sub}}^{0.499} \quad \text{(for open bottoms)}, \tag{2a}$$

$$h_{\text{b}} = 0.266q''^{0.896}/s^{0.305}\Delta T_{\text{sub}}^{0.115} \quad \text{(for closed bottoms)}. \tag{2b}$$

At both subcooled and saturated boiling regions:

$$h_{\text{b}} = 0.548q''^{0.842}/s^{0.159}e^{0.075\Delta T_{\text{sub}}} \quad \text{(for open bottoms)}, \tag{3a}$$

$$h_{\text{b}} = 0.695q''^{0.817}/s^{0.241}e^{0.022\Delta T_{\text{sub}}} \quad \text{(for closed bottoms)}. \tag{3b}$$

In the above equations, the dimensions for h_{b}, q'', s, and ΔT_{sub} are kW/m^2 °C, kW/m^2, mm, and °C, respectively. Apparently the correlations only apply for the testing pressure and parameters shown in Table 2. The above

Table 3
Statistical analysis on $\frac{h_{\text{b,measured}}}{h_{\text{b,calculated}}}$ data

Fluid condition	Bottom condition	Mean	Standard deviation
Single phase	Open	1.016	0.079
	Closed	1.004	0.048
Pool boiling	Open	1.025	0.170
	Closed	0.955	0.220

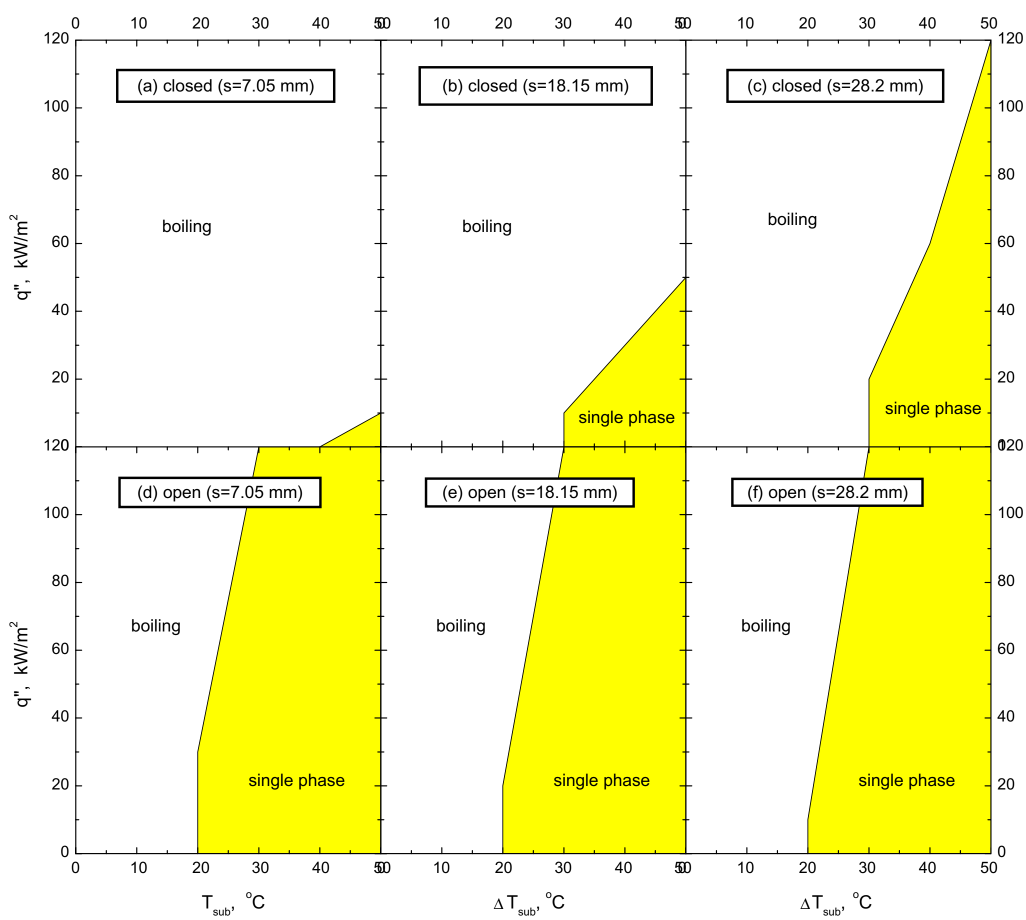

Fig. 4. Regions of single phase and boiling heat transfer.

correlations are only applicable for water on a stainless steel surface. The results of the statistical analyses on the measured and the calculated data are listed in Table 3.

4. Results and discussion

Relation between the heat flux and the tube wall superheat is shown in Fig. 5 as functions of the liquid subcooling and the gap size. To elucidate effects of the annuli on heat transfer results of the annuli were compared with the results of the single unrestricted tube. As shown in the figure every data of the single tube and the annuli with open bottoms are at the single-phase heat transfer region at $\Delta T_{sub} \leqslant 30$ °C. Curves of q'' versus ΔT_{sat} show similar tendency for the single tube and the annuli with open bottoms. The dramatic phenomenon arises at the annuli with closed bottoms. Several data points are at the saturated regions as the degree of subcooling is 50 °C. As $s = 7.05$ mm, almost every data is in the saturated region. At $\Delta T_{sub} = 30$ °C, almost every data for the closed bottoms are located at the saturated region. Therefore, the major mechanisms for the annuli with closed bottoms can be presumed to be different from the single tube and the annuli with open bottoms. The scattering of the tube wall is observed to be high at $\Delta T_{sub} = 50$ °C and $s = 7.05$ mm. This was originated from the earlier liquid saturation and very complex bubble movement.

For visual observation several photos of boiling on the surface have been taken and shown in Figs. 6 and 7. Every photo was taken at the level of the thermocouple 2 of the heated tube. Several photos at $s = 7.05$ mm have been compared. Boiling on the tube surface in the annuli with open bottoms is similar to the single unrestricted tube [15]. Very small tiny bubbles (about 1–2 mm) are observed nearby the tube surface at $\Delta T_{sub} = 20$ °C. As the degree of subcooling decreases the size of the bubbles become increased. Since more nucleation sites are expected as the heat flux increases, more bubbles are observed at higher heat fluxes. Therefore, it might be explained that the intensity of agitation due to the departed bubbles is almost negligible in the highly subcooled liquid and gets increased as the liquid becomes saturated. Although the general tendency of boiling on the surface for the annuli with open bottoms is similar to the single tube, earlier bubble generation and bigger size is observed for the annuli. This is related with the space where effects of liquid agitation are affected on. Since pool boiling in the annulus with closed bottom is not steady, but is frequent [14,15], several photos of boiling on the tube surface have been taken for the first 3 s and shown in Fig. 7. As the

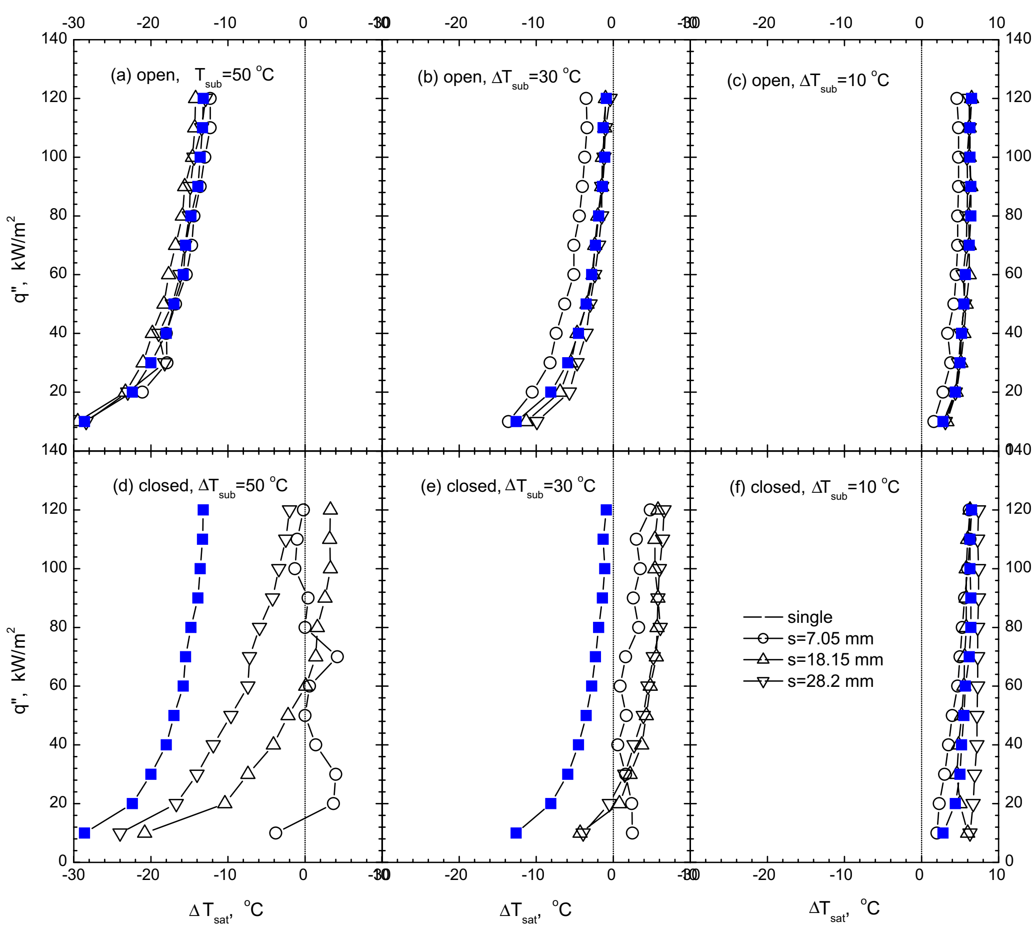

Fig. 5. Curves of q'' versus ΔT_{sat} as s and ΔT_{sub} change.

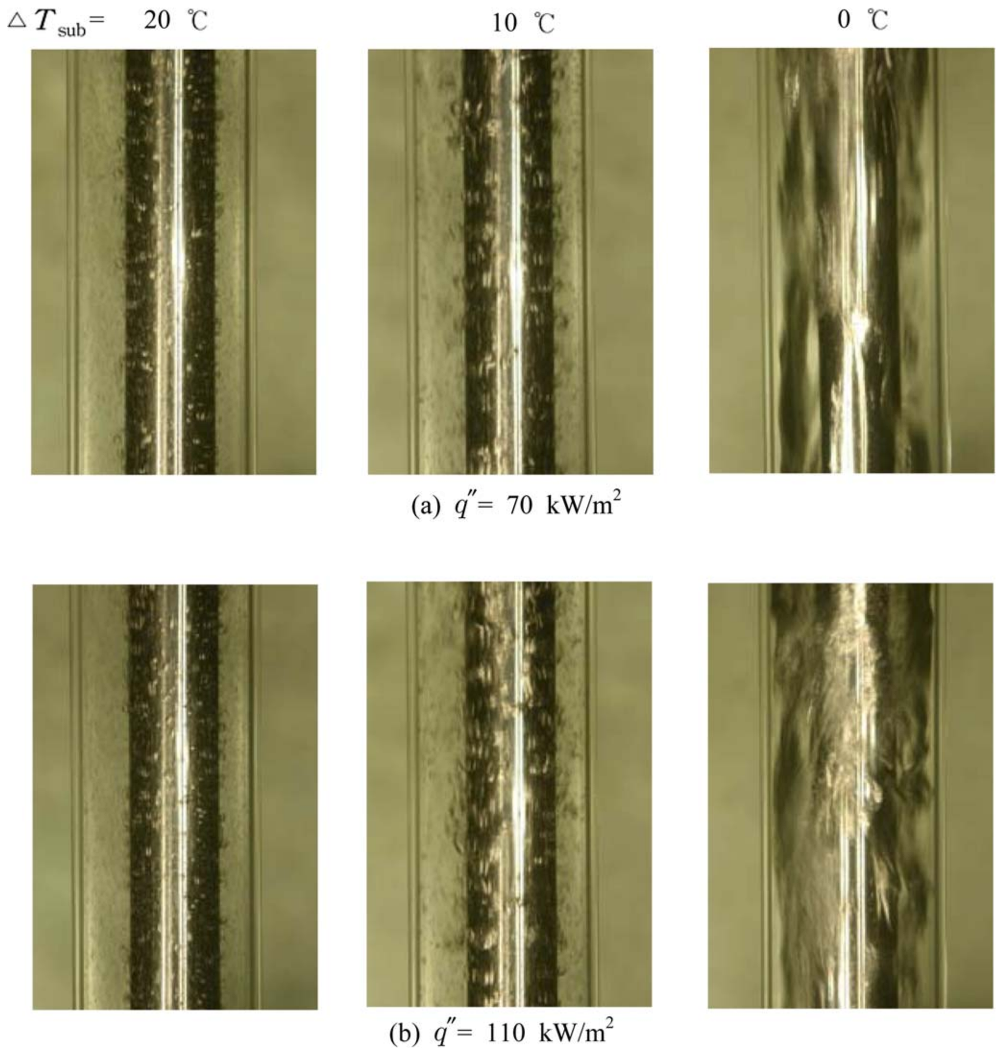

Fig. 6. Photos of boiling in annulus with open bottoms ($s = 7.05$ mm).

heat flux gets higher the bubble bunches are more frequently observed in the space. Big bunches of bubbles are observed even at lower heat flux. Only small bubbles are observed at first and, then, sudden creation of many bubbles is started from the bottom region of the tube. The bubbles generate big slugs in the space and move to the upper end side sweeping over the heated tube surface. After the bubble slugs escaped from the space there would be abrupt liquid rush to the space from the environment. As the $T_W - T_b$ increases more than 0 °C, a sudden creation of bubbles starts again. This series of procedure generates a kind of pulsating flow of bubbles and liquid in the annular space. Therefore, very active agitation is expected at the annuli with closed bottoms. The period depends on the heat flux and the subcooling. The higher subcooling and lower heat fluxes result in a longer time of oscillation. As the degree of subcooling is decreased, the generation of bubbles gets more frequent and, then, the bubble slugs cover almost every space in the annulus. It can be suggested that the dominant heat transfer mechanism is closely related with the active liquid agitation at highly subcooled region. Thereafter, the mechanism changes to bubble coalescence on the surface as the liquid in the pool gets saturated.

Fig. 8 shows changes in heat transfer coefficients as the heat flux changes. Both results of the annuli with open or closed bottoms are depicted at the same gap size and the subcooling. For the annuli with open bottoms h_b is linearly increasing as q'' increases regardless of the gap size and the liquid subcooling. However, results for the annuli with closed bottoms show somewhat different tendency. As $s \geqslant 18.15$ mm h_b changes almost linearly as q'' increases like the open bottoms. However, at $s = 7.05$ mm curves of h_b versus q'' show different shapes comparing with the other cases. In general, heat transfer coefficients for the annuli with closed bottoms are greater than the values for the annuli with open bottoms. The difference is magnified at $10\ °C \geqslant \Delta T_{sub}$. At these subcooling the intensity of liquid agitation is very strong. Since active bubble movement is created in the annuli with closed bottoms as shown in Fig. 7, heat transfer coefficients for the closed bottoms are much greater than the coefficients for the open bottoms. However, as the heat flux increases more than 100 kW/m^2

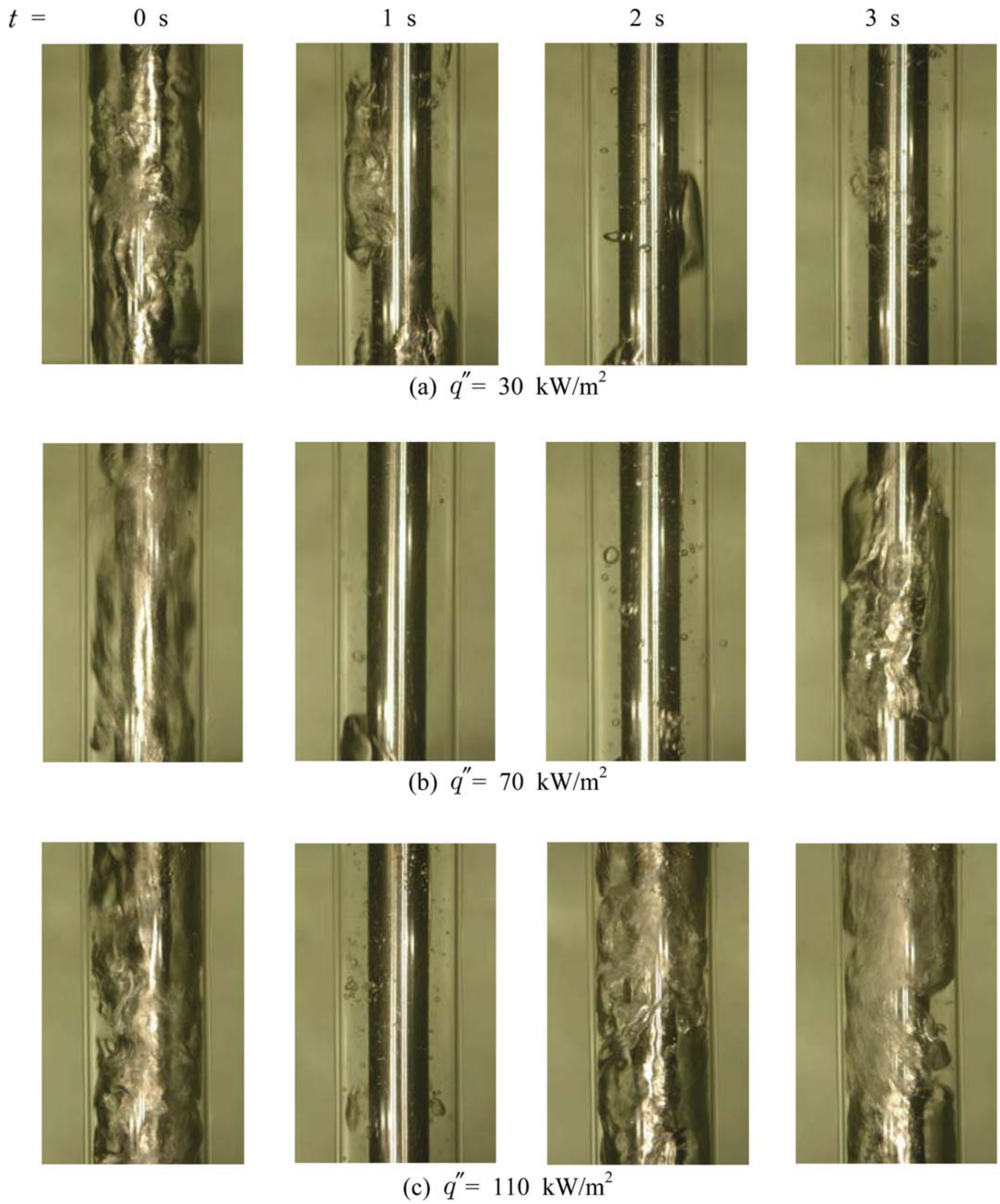

Fig. 7. Photos of boiling in annulus with closed bottoms at $\Delta T_{\text{sub}} = 20$ °C and $s = 7.05$ mm.

a deterioration of the heat transfer coefficient is observed at $s = 7.05$ mm. This is because of the bubble coalescence on surface of the tube [15]. The intensity of the bubble coalescence is magnified at $\Delta T_{\text{sub}} = 0$ °C and $s = 7.05$ mm. At this condition the heat transfer coefficients for the closed bottoms are less than the coefficients for the open bottoms. Throughout the cases, regardless of the bottom conditions, heat transfer coefficients are increased because of (1) ΔT_{sub} decrease, (2) q'' increase, and (3) s decrease except some data points for the heat fluxes larger than 100 kW/m^2 at $s = 7.05$ mm. However, effects of the gap size on the heat transfer coefficient in the annuli with open bottoms are not significant except near the saturation point. As ΔT_{sub} decreases from 50 to 0 °C at $q'' = 100$ kW/m^2 and $s = 18.15$ mm, 506% (from 3.2 to 19.4 kW/m^2 °C) and 302% (from 4.7 to 18.9 kW/m^2 °C) increases in heat transfer coefficients are observed for the open and closed bottoms, respectively. Similarly, as s decreases from 28.2 to 7.05 mm at $q'' = 110$ kW/m^2 and $\Delta T_{\text{sub}} = 20$ °C, −2% (from 5.2 to 5.1 kW/m^2 °C) and 122% (from 7.4 to 16.4 kW/m^2 °C) increases in heat transfer coefficients are observed for the open and closed bottoms, respectively.

To identify changes in heat transfer coefficients by the introduction of the annuli, local heat transfer coefficients for the annuli were compared with the values of the single tube. The ratios of $h_{\text{b,annulus}}/h_{\text{b,singletube}}$ for the three locations are depicted in Fig. 9. For the open bottoms the ratios are generally nearby 1 except the data of the saturation. Ratios of T/C1 and T/C5 are larger than that of T/C3 due to the activated bubbles and the circulating flow,

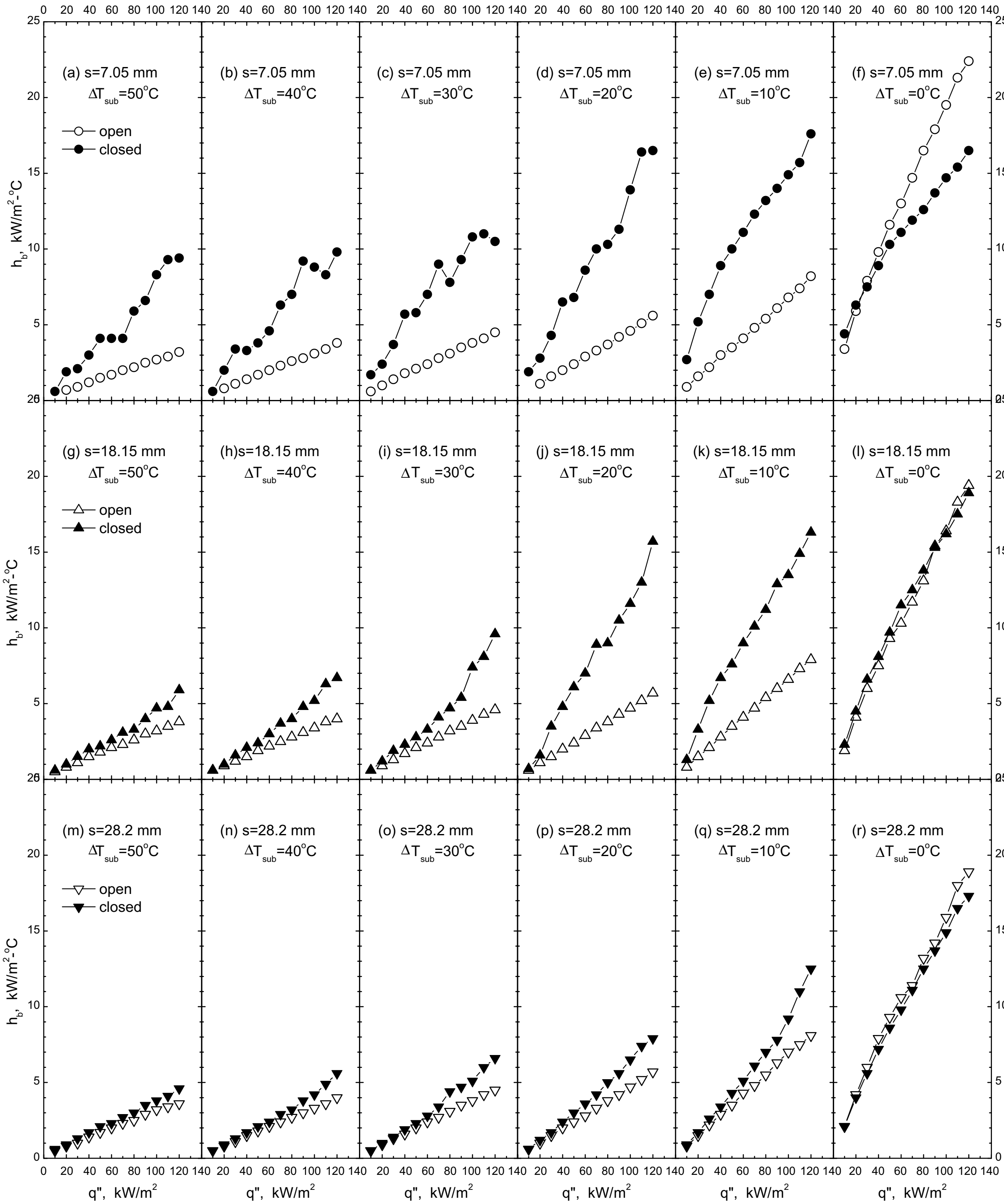

Fig. 8. Variations in heat transfer coefficients as heat flux and subcooling change.

respectively. One of the effective ways to increase heat transfer is the circulating flow in the tank [7]. Because of the flow heat transfer at the bottom region of a vertical tube can be changed much. For the annuli with open bottoms this effect is magnified due to the narrower flow area. Therefore, the ratio at T/C5 is high in the saturated water. For the closed bottoms the ratios are greater than the open bottoms. The ratio is magnified as the gap size decreases. As $10°\mathrm{C} \leqslant \Delta T_{\mathrm{sub}} \leqslant 30\ °\mathrm{C}$ at $s = 7.05$ mm the ratio is between 2 and 6. At $\Delta T_{\mathrm{sub}} = 0\ °\mathrm{C}$ the ratio is converging to 1 as the heat flux increases. The most dramatic change in the ratio is observed at $\Delta T_{\mathrm{sub}} \geqslant 40\ °\mathrm{C}$ and $s = 7.05$ mm. This denotes the rapid increase in the intensity of active liquid agitation. As the heat flux increases and the gap size decreases the ratio becomes decreasing because of the bubble coalescence. This is clearly observed at the

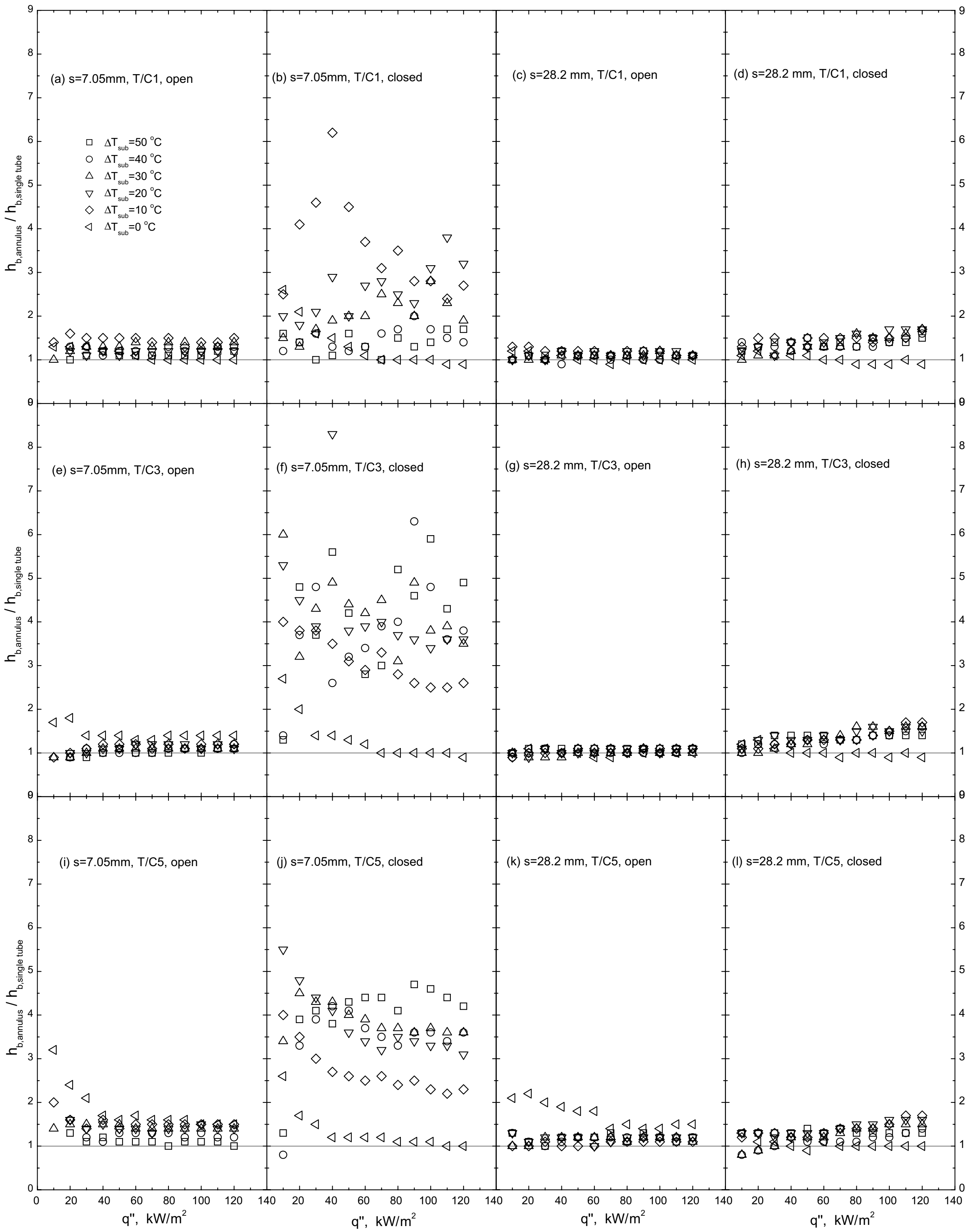

Fig. 9. Plots of $h_{b,annulus}/h_{b,singletube}$ versus q'' at local points on tube surface in annuli with open or closed bottoms.

location of T/C1. The ratios for T/C3 are slightly larger than values for the other two thermocouples. This shows the regions of the strong liquid agitation for the annuli with closed bottoms are nearby the mid length of the tube. At the location of T/C1 the outflow of bubbles is disturbed by the inflow of the liquid. Therefore, deterioration of heat transfer coefficients is clearly observed around the top regions of the tube even at highly subcooled liquid.

Fig. 10 shows a comparison of the measured and the calculated heat transfer coefficients by Eqs. (2a) and (2b) at

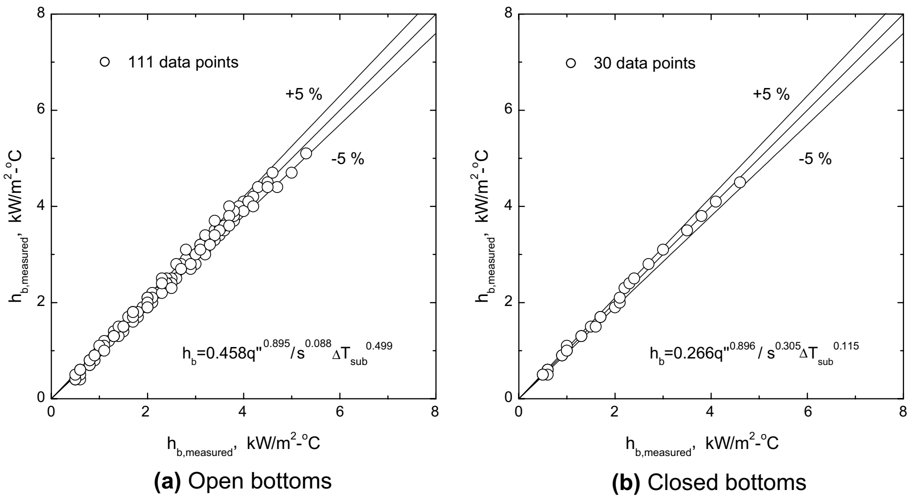

Fig. 10. Comparison of measured data with calculated values at single phase regions.

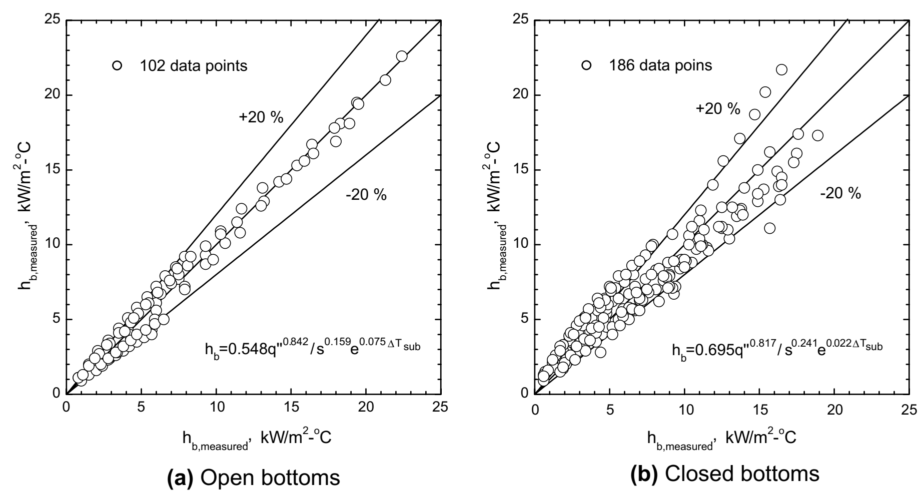

Fig. 11. Comparison of measured data with calculated values at boiling regions.

the single-phase region. Both heat transfer coefficients for the annuli with open or closed bottoms are plotted. The developed empirical correlations predict the experimental data within ±5% error bound. A comparison of the coefficients at boiling regions is shown in Fig. 11. Both data of subcooled and saturated boiling are plotted together. This figure indicates that the scatter of the present experimental data is within ±20%, with some exceptions from the fitted data of Eqs. (3a) and (3b). This is because of the complex heat transfer mechanisms in the annuli [14]. The scattering bound is much wider at the annuli with closed bottoms since the boiling mechanism for the case is much complex than the annuli with open bottoms. The flow in an annulus with open bottoms is steady while the flow in an annulus with closed bottoms are pulsating. Moreover, earlier active boiling is expected at the closed bottoms [14]. The scatter of the present data is of similar size to that found in other existing pool boiling data. As noted by others [8], 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.

Comparisons of the experimental data of h_b versus q'' with the calculated values are shown in Fig. 12. Several data of different gap sizes and subcooling are compared at the regions of single-phase, subcooled boiling, and saturated boiling. Predictions made by the above correlations are shown by solid (for closed bottoms) and dotted (open bottoms) lines. The measured data is near the fitted curves of Eqs. (2a)–(3b). The fitness is good for the data of the single-phase heat transfer regions. At both subcooled and saturated boiling regions the prediction is good for the data of the annuli with open bottoms. However, the correlations for the closed bottoms slightly under predict the experimental data. Although some discrepancies are observed at the boiling data for the annuli with closed bottoms, the difference is of acceptable with considering the inherent characteristics of the boiling heat transfer. Fig. 13 shows

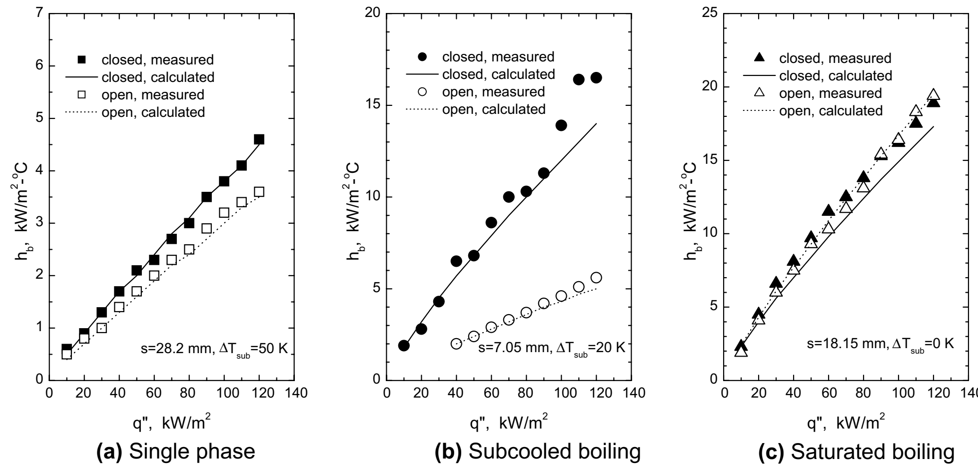

Fig. 12. Comparison of measured data with calculated values.

general tendency of the experimental data and the predictions made by the above correlations. Experimental data of h_b versus ΔT_{sat} throughout the regions of single phase, subcooled boiling, and saturated boiling are plotted together in a graph. The connection between the calculated heat transfer coefficients at single phase and boiling regions

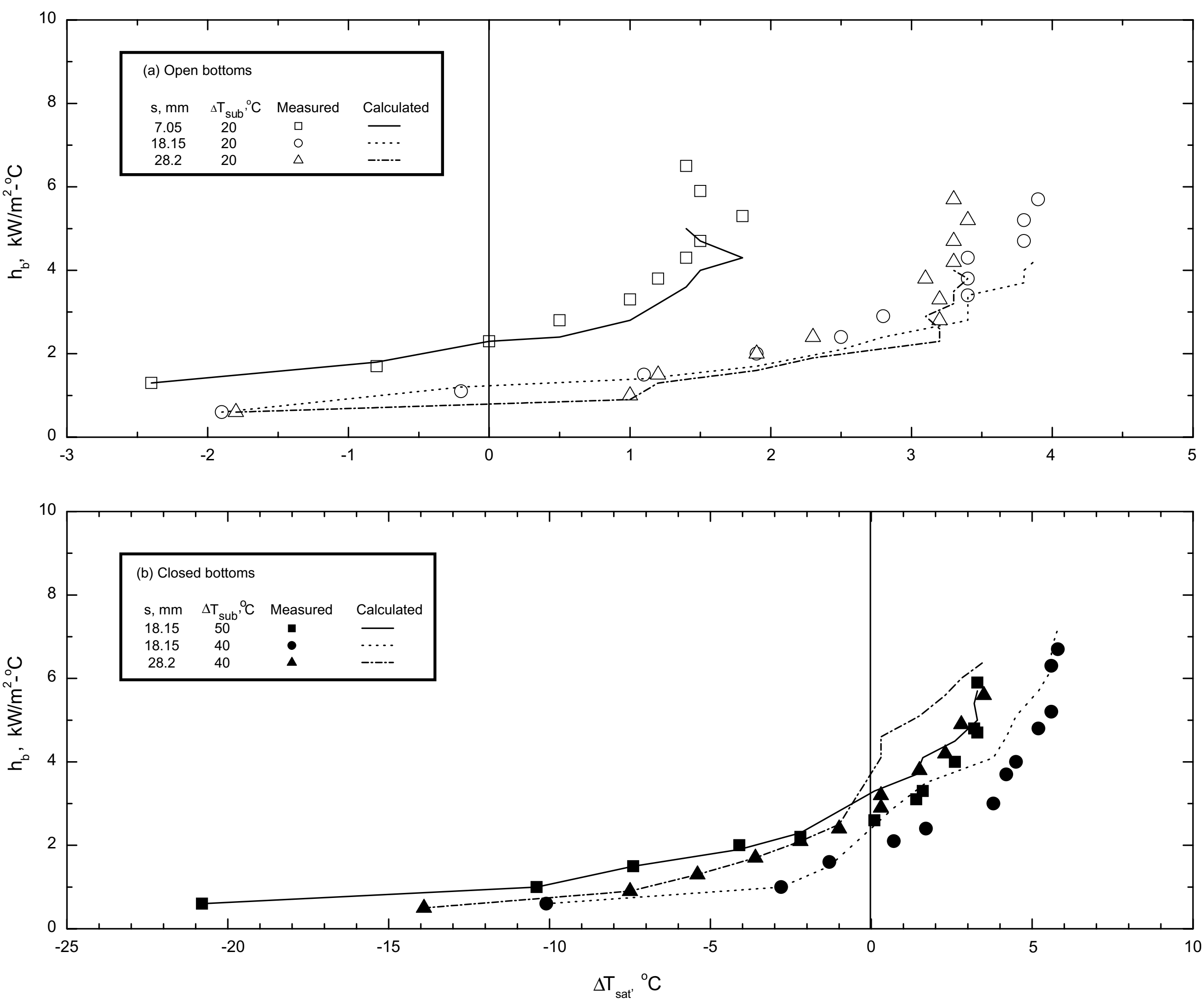

Fig. 13. Curves of h_b versus ΔT_{sat} for combined data.

are very smooth. Moreover, the predictions by the correlations are reasonable and to be acceptable. Therefore, it can be concluded that the developed correlations are valuable to predict heat transfer coefficients at single phase or boiling regions in the annuli with open or closed bottoms.

5. Conclusions

To identify the effects of liquid subcooling on pool boiling heat transfer of water at atmospheric pressure, three annuli (gap size: 7.05, 18.15, and 28.2 mm) with open or closed bottoms in the vertical direction have been studied experimentally. In addition, the results were compared with those of an unrestricted single tube. The major conclusions of the present study are as follows:

1. Regardless of the bottom conditions, heat transfer coefficients are increased because of ΔT_{sub} decrease, q'' increase, and s decrease except some data points for the heat fluxes larger than 100 kW/m^2 at $s = 7.05$ mm.
2. At the annuli with closed bottoms higher heat transfer coefficients are observed at higher subcooling. However, a deterioration of heat transfer coefficients is observed as the degree of subcooling decreases.
3. The major heat transfer mechanisms for the single tube and the annuli with open bottoms are suggested as single-phase natural convection and liquid agitation at $\Delta T_{\text{sub}} > 10$ °C and $\Delta T_{\text{sub}} \leqslant 10$ °C, respectively. For the annuli with closed bottoms liquid agitation is the governing mechanism at $\Delta T_{\text{sub}} > 10$ °C and the governing mechanism changes to bubble coalescence at $\Delta T_{\text{sub}} \leqslant 10$ °C.
4. Four empirical correlations for the heat transfer coefficient have been suggested in terms of the gap size, the degree of subcooling, and the heat flux. Two are to predict heat transfer coefficients in single-phase regions. The other two are for both subcooled and saturated boiling regions. The correlations predict the data of single phase and of boiling heat transfer within $\pm 5\%$ and $\pm 20\%$, respectively.

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