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Technical Note

Pool boiling heat transfer in vertical annular crevices

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Abstract

Effects of vertical annuli on nucleate pool boiling heat transfer of water at atmospheric pressure have been obtained experimentally. Experiments were performed for annuli with a height of 570 mm and gap sizes of 3.9 and 15 mm. Through the tests, tube bottom confinement (open or closed) has been investigated, too, and the whole results are compared with a single unconfined tube. According to the results, the annular condition gives much increase in heat transfer coefficients at moderate heat fluxes. Its effect is observed much greater for the bottom-closed tube condition. © 2002 Elsevier Science Ltd. All rights reserved.

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 the advanced light water reactors [1,2].

Studies on the crevices can be divided into two categories. One of them is about annuli [3,4] and the other one is about plates [5,6]. Some geometry has closed bottom [3,5]. It is well known from the literature that the confined boiling can result in heat transfer improvements up to 300–800% at low heat fluxes, as compared with unconfined boiling [3,5]. However, a deterioration of heat transfer appears at high heat fluxes for confined than for unrestricted boiling [5,6]. Summarizing the previous works about crevice effects on pool boiling heat transfer (see Table 1) it can be concluded that the amount of the heat transfer coefficient (h_b) is highly dependent on the geometry and confinement condition.

Through the literature survey, it can be concluded that studies about both annuli with open bottom and longer heating surface are necessary. One of the most important factors in heat exchangers design for application to the advanced light water reactors is to find a way to increase heat transfer coefficients [1] and those heat exchangers have usually very lengthy heat exchanging tubes. Therefore, to investigate the potential areas for improvement of the thermal design of the heat exchangers and to add some data on the previous works by others, nucleate pool boiling heat transfer in annuli and tubes of water has been investigated at atmospheric pressure.

2. Experiments

A schematic view of the present experimental apparatus and test sections is shown in Fig. 1. The water storage tank is made of stainless steel and has a rectangular cross-section (600×600 mm^2) and a height of 800 mm. This tank has a glass view port (500×700 mm^2) which permits viewing of the tubes and photographing. To reduce heat loss to the environment, every wall, except the front side, of the tank were insulated by glass wool of 30 mm in thickness. The heat exchanger tubes are simulated by resistance heaters of very smooth cold-drawn stainless steel tubes ($L = 570$ mm and $D = 25.4$ mm).

The surface temperatures of the tube were instrumented with five T-type sheathed thermocouples (diameter is 1.6 mm) outside the surface of the tube. The thermocouple tip (about 10 mm) has been bent at a 90°

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Nomenclature

B_o	bond number	q''	heat flux
D	tube outer diameter	s	gap size of the annulus
D_i	inside diameter of the outer tube	T_{sat}	saturated water temperature
h_b	boiling heat transfer coefficient	T_W	tube wall temperature
L	tube length		

angle and brazed the bent tip on the tube wall. The locations of the thermocouples are 85, 180, 285, 385, and 485 mm from the tube bottom. The water temperatures were instrumented with seven sheathed T-type thermocouples placed at the tank wall vertically from the tank bottom with equal space (i.e., 100 mm). All thermocouples were calibrated at the boiling point.

For the tests, the heat exchanging tubes are placed at the tank bottom and a tube supporter of 140 mm in outer diameter is used to fix the glass tubes. To make open or closed bottom conditions, glass tubes (600 mm in length) having inside diameters (D_i) of 33.3 and 55.4 mm were used. Therefore, gap sizes (s) of the annuli are 3.9 and 15 mm and Bond numbers (B_o) for the cases are 1.56 and 5.99, respectively. The side with holes is placed at the tank bottom for the open bottom tests. In other words, the side without holes is placed at the tank bottom for the closed bottom tests.

After the water storage tank is filled with water until the initial water level is reached at 730 mm, the water is then heated using three pre-heaters at constant power (i.e., 5 kW/heater). When the water temperature is reached at 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 min 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 uncertainty in the heat flux and the measured temperature is estimated to be ±1.0% and ±0.5 K, respectively. The uncertainty for the temperature includes errors from thermocouple compensation, multiplexer, and thermocouple sensing. The uncertainty of the calculated heat transfer coefficients (i.e., $h_b = q''/\Delta T$) depends on the superheat ($\Delta T = T_W - T_{sat}$) and heat flux (q''). It is ±12.5% as $q'' = 80$ kW/m^2 and $\Delta T = 5$ K.

Table 1
Previous works about crevice effects on pool boiling heat transfer

Author	Remarks
Yao and Chang [3]	• Heater: stainless steel tube ($D = 25.4$ mm, $L = 25.4$ and 76.2 mm) • Liquid R-113, acetone, and water in 1 atm • Geometry: vertical annuli with closed bottoms • Gap sizes: 0.32, 0.80, and 2.58 mm
Hung and Yao [4]	• Heater: stainless steel tube ($D = 25.4$ mm, $L = 25.4$–76.2 mm) • Liquid R-113, acetone, and water in 1 atm • Geometry: horizontal annuli • Gap sizes: 0.32, 0.80, and 2.58 mm
Fujita et al. [6]	• Heater: copper plate (30 × 30 and 30 × 120 mm^2 in width × length) • Liquid water in 1 atm • Geometry: ○ Vertical and inclined spaces between rectangular surfaces ○ Periphery; open; closed sides, closed sides and bottom • Gap sizes: 0.15, 0.60, and 5.0 mm
Bonjour and Lellemand [5]	• Heater: copper plate (60 × 120 mm^2 in width × length) • Liquid: R-113 at 1 atm • Geometry: ○ Vertical and inclined spaces between rectangular surfaces ○ Periphery; sides and bottom are left open • Gap sizes: 0.3, 0.50, 1.0 and 2.0 mm

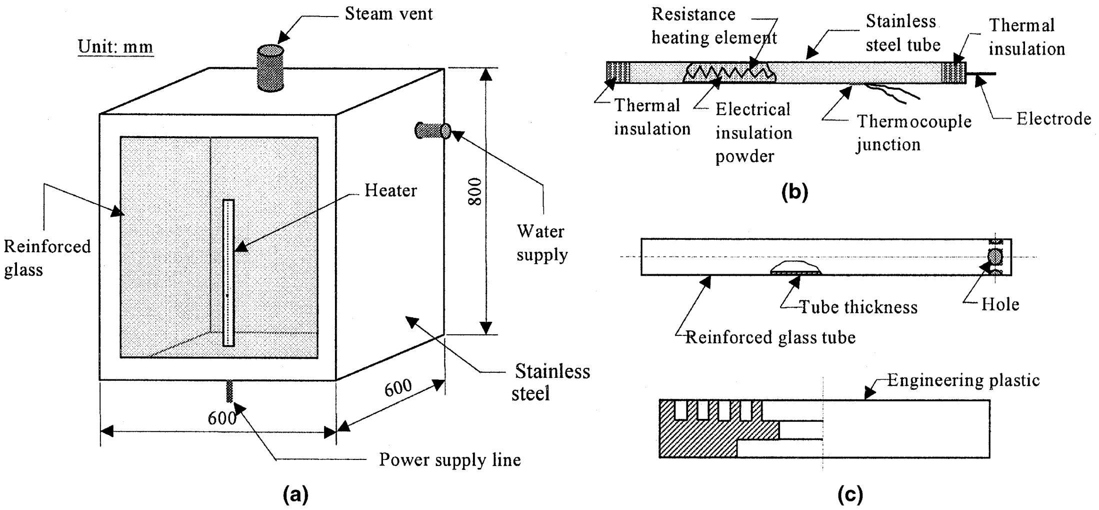

Fig. 1. Schematic diagram of the experimental apparatus. (a) Water tank, (b) heated tube, (c) glass tube and tube supporter.

3. Results and discussion

The experimental results for the annuli with open or closed bottoms are shown in Fig. 2. For the open bottom (i.e., Fig. 2(a) and (b)), the general trend is similar to those of the unrestricted tube [1]. However, as the gap size gets smaller the curve for q'' versus ΔT shows to be linear. As the space gets narrower much larger bubbles

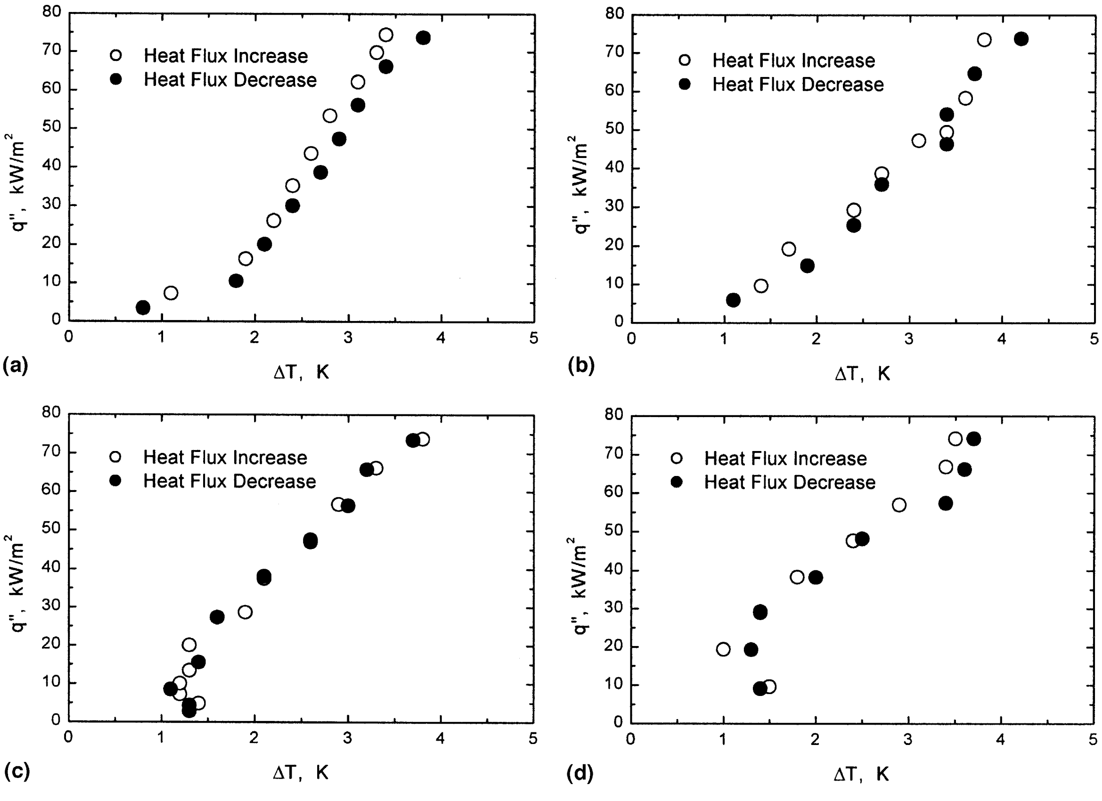

Fig. 2. Heat flux versus tube wall superheat: (a) open bottom, $s = 15$ mm; (b) open bottom, $s = 3.9$ mm; (c) closed bottom, $s = 15$ mm; (d) closed bottom, $s = 3.9$ mm.

are generated and the intensity of liquid agitation due to bubble departure gets stronger. Since the departed bubbles not go far from the heating surface for the confined tubes, these bubbles agitate relevant liquid very much and increase heat transfer rate. Once the bottom side is closed, very strong liquid agitation and, accordingly, sudden decrease in tube wall superheat is observed at low heat flux. As the space gets narrower the curve for q'' versus ΔT shows almost a reverse S-curve (see Fig. 2(d)). For the case of the closed bottom, more complicated bubble and liquid mixing is observed than the case of the open bottom since liquid should enter the upper side as the bubbles get out from it. These bubbles coalesced together and move upward and downward. Therefore, very active bubble agitation can be observed. Values of heat fluxes when $s = 3.9$ mm and $\Delta T = 2$ K

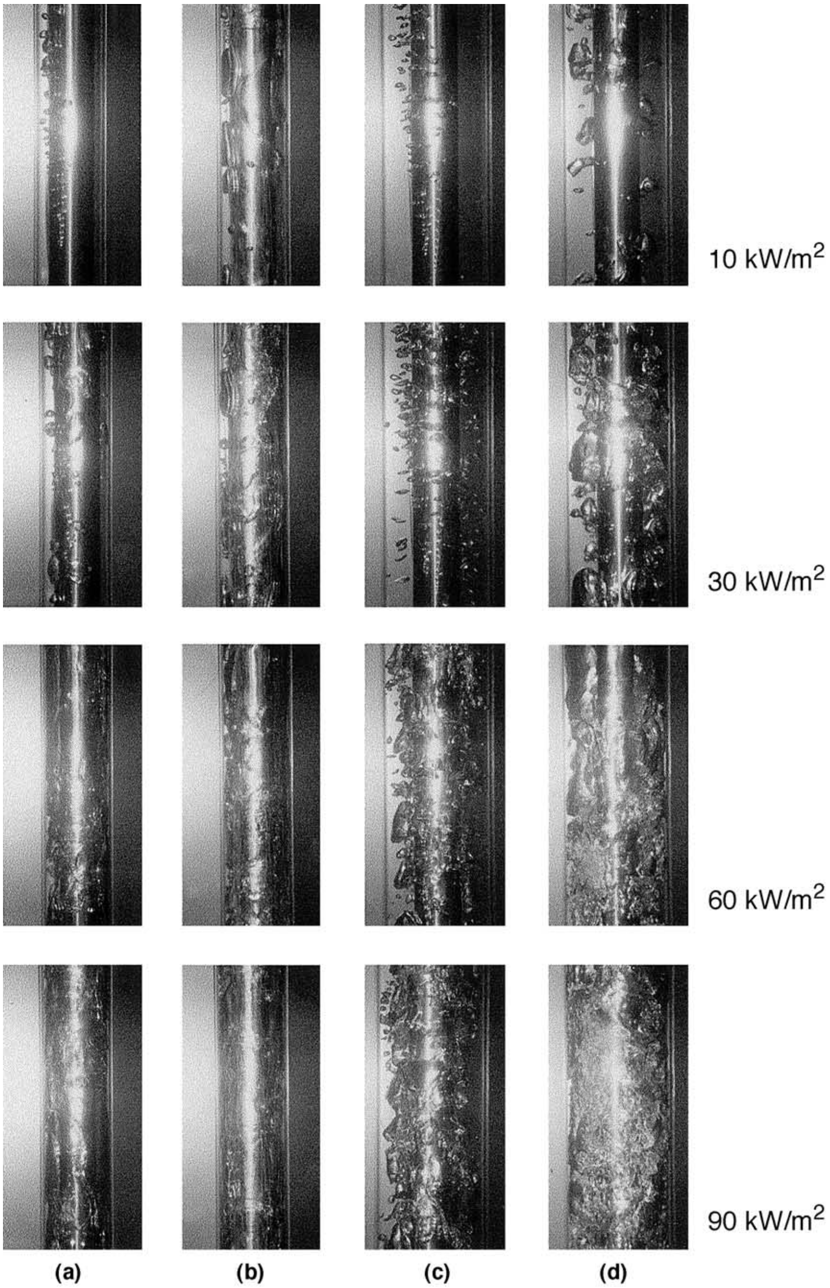

Fig. 3. Some photos taken for the annuli: (a) open bottom, $s = 3.9$ mm; (b) closed bottom, $s = 3.9$ mm; (c) open bottom, $s = 15.0$ mm; (d) closed bottom, $s = 15.0$ mm.

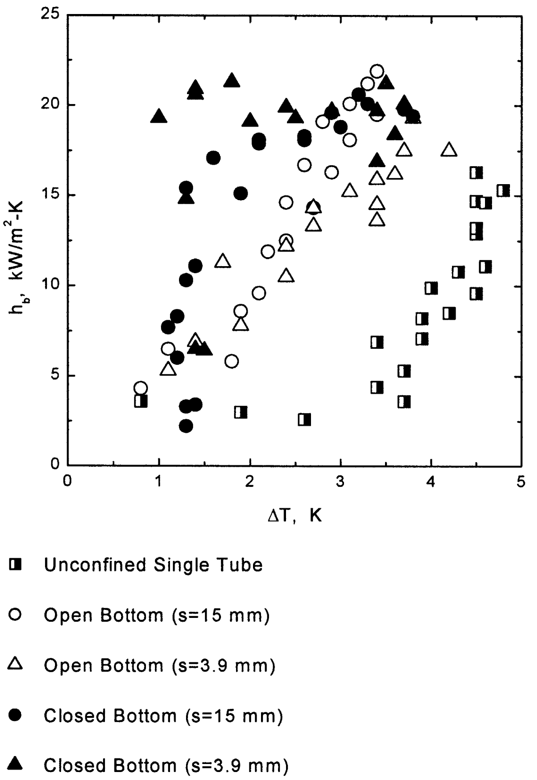

Fig. 4. Heat transfer coefficient versus tube wall superheat for various tube conditions.

are 15 and 40 kW/m^2 for the open and closed bottom, respectively. Therefore, the heat flux for the closed bottom case is 2.7 times greater than that for the open bottom case. However, the decrease in the gap space from 3.9 to 15.0 mm gives no significant change in heat transfer.

Fig. 3 shows some photos of the annuli boiling as q'' and s change. As shown in the figure, the open bottom has higher liquid in-flow and gives smaller bubbles and lower void fraction. However, the closed bottom has restricted net-flow of liquid and the bubbles are larger and void fraction is high. For the closed bottom, fluid chugging was also observed. Those photos were taken at around the mid-point of the tube length. As shown in the photos very early bubble coalescence is observed for the closed bottom conditions. The deformed bubbles also observed for the closed bottom of $s = 3.9$ mm (i.e., $B_o = 1.56$) even at a lower heat flux.

Fig. 4 shows results of h_b versus ΔT for various tube conditions. As shown in the figure, annuli conditions result in much increase in heat transfer coefficient comparing with the unconfined single tube. Comparing the heat transfer coefficient for the closed bottom tube ($s = 3.9$ mm) with the unconfined tube at $\Delta T = 1.5$ K, the former one has almost nine times greater than the last one. Once the tube bottom is closed, a very rapid increase in h_b is observed at low wall superheat (less than $\Delta T = 2$ K). Increasing ΔT more than 2 K for the bottom-closed case h_b has almost a same value (i.e. about 20 kW/m^2 K) regardless of the heat flux increase. This is due to narrower bubble exit. Since liquid must come into the gap space through the upper side of the glass tube, this prevents bubble escape from the tube exit. Therefore, much bigger bubbles can be formed on the tube surface to decrease heat transfer rate. For the open bottom case, much smoother curve gradient is expected as the gap size decreases and the heat flux increases.

4. Conclusions

The major conclusion drawn from this experimental investigation may be stated that the annular condition gives much increase in heat transfer coefficients at moderate heat fluxes and its effect is observed much greater for the bottom-closed tubes.

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