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A suggestion to enhance pool boiling heat transfer on a vertical tube surface †

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Abstract

To find a way of improving pool boiling heat transfer on a vertical tube surface, a revised annulus has been investigated experimentally. The annulus with closed bottoms has a shorter outer tube than the inside heated tube. For the study, three tube diameters (16.5, 19.1, and 25.4mm) and water at atmospheric pressure were used. The annular gap covers from 3.2 to 19.3mm in size and is generated by several glass tubes, which are fabricated around the heated tube. To clarify effects of the revised annulus on heat transfer, experimental results of the annulus were compared to the data of unrestricted tubes. The heat transfer coefficients for the revised annulus increased remarkably in comparison to the unrestricted tube.

Keywords: Annulus; Heat transfer enhancement; Pool boiling; Vertical tube

1. Introduction

The mechanism of pool boiling heat transfer has been studied for the past several decades since it is closely related to the thermal design of more efficient heat exchangers [1]. The thermal efficiency of a heat exchanger is important if the space for the heat exchanger installation is very limited as with advanced light water reactors [2]. One of the effective means to increase heat transfer is to consider a confined geometry. Major geometries concerning about the crevices are annuli [3-5] and plates [6, 7]. Some geometry has closed bottoms [3, 5, 6].

It is well known from the literature that confined boiling can result in heat transfer improvement up to 300%-800% at low heat fluxes (q''), as compared with unconfined boiling. However, a deterioration of heat transfer appears at higher heat fluxes for confined boiling [3, 5]. According to Kang [5] once flow inlet holes at the bottom region of an annulus are closed, a remarkable increase in the heat transfer coefficient (h_b) is observed as the heat flux increases at low wall superheat (ΔT_{sat}) less than 2℃. However, at $\Delta T_{sat} \geq 2$℃ the coefficient has almost the same value (i.e., about 20 kW/m²-℃) regardless of the heat flux. The cause of the heat transfer deterioration is suggested as bubble coalescence at the upper region of the annulus [3]. To apply a vertical annulus with closed bottoms to the thermal design of a heat exchanger, more study to remove the deterioration is inevitable.

Up to the author's knowledge, no previous results concerning the deterioration in an annulus have been published yet except for the author's preliminary study. Recently, Kang [8] published some results of the vertical annulus (19.5 mm tube diameter; 3.7, 6.4, and 18.0 mm annular gap, s) with closed bottom inlets. Kang [8] controlled the length of the outer tube (L_o) of the annulus and identified that the change of L_o resulted in much variation in heat

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transfer. In the study one of the efficient outer tube lengths was 0.2 m. Therefore, the present study is focused on a revised annulus, which having L_o=0.2 m. To clarify the improvement in heat transfer due to the adoption of the revised annulus and to amplify its applicability to the thermal design of heat exchangers, more study of the other gap sizes and the different tube diameters is needed. The present study is aimed at the extension of Kang's previous results to other geometries through changing the gap size and the heated tube diameter.

2. Experiments

A schematic view of the present experimental apparatus and the test section is shown in Fig. 1. The outer 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 size of the inner tank is 800×1000×1100 mm (depth×width×height). The inner tank has several flow holes (28 mm in diameter) to allow fluid inflow from the outer tank. Four auxiliary heaters (5 kW/heater) were installed at the space between the inner and the outer tank bottoms. The heated tube (Fig. 1(b)) is made of a very smooth stainless steel tube (length, L=0.54 m; tube diameter, D=16.5, 19.1, and 25.4 mm). Several rows of resistance wires are arrayed uniformly inside the heated tube to supply power to the tube. Both sides of the tube are thermally insulated to prevent any possible heat loss through the ends. The surface of the tube is finished through the buffing process to have a smooth surface. Electric power of 220 V AC is supplied through the bottom side of the tube.

The tube outside is instrumented with five T-type sheathed thermocouples (diameter is 1.5 mm). The thermocouple tip (about 10 mm in length) is brazed on the tube surface. The water temperatures are measured with six sheathed T-type thermocouples placed at the tank wall vertically from the bottom of the inner tank with equal spacing (i.e., 180 mm). All thermocouples are calibrated at a saturation value. To measure and/or control the supplied voltage and current, two power supply systems are used. The capacity of each channel is 10 kW.

For the tests, the heat exchanging tube is assembled vertically on the supporter and an auxiliary tube supporter is used to fix a glass tube. To make the annular condition, three glass tubes of the same axial length (L_o=0.2 m) are used. A fixture made of slim wires is

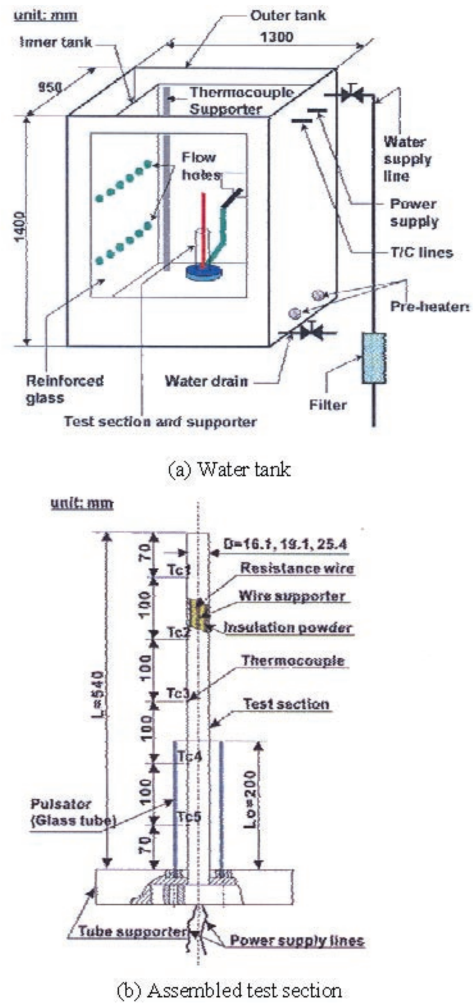

Fig. 1. Schematic of experimental apparatus.

inserted into the upper side of the annulus to maintain the space between the heated tube and the glass tube. As a result, several gap sizes covering from 3.2 to 19.3 mm have been generated by the combination of the heated tube and the outer glass tube.

After the tank is filled with water until the initial water level is reached at 1100 mm, the water is then heated by 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 the heat flux on the tube surface is controlled with input power. Once a set of experiments has been performed for various heat fluxes, a series of experiments is performed for the other annular gap. The single unrestricted tube is tested at first, and then the annulus is tested.

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

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

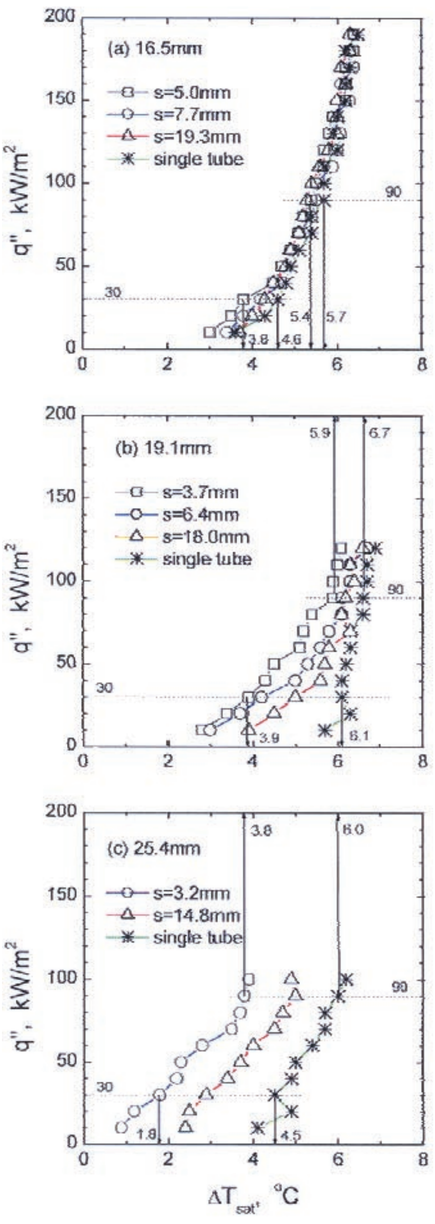

Fig. 2. Plots of q'' versus ΔT_{sat} data.

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 value of the temperatures measured by thermocouples.

The uncertainty in the heat flux is estimated to be ±1.0%. 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 tests took less than 1 hour, the elapsed time to estimate the uncertainty of the thermocouple probes was set as 1 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 converted 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 and its 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

Figs. 2(a), 2(b), and 2(c) are q'' versus ΔT_{sat} curves for the three different tube diameters when the gap size is used as a major test parameter. In these figures the following observations can be made:

(1) The existence of the annuli results in the decrease in ΔT_{sat} at a given heat flux regardless of the tube diameter. When s =3.7 mm and D =19.1 mm, ΔT_{sat} gets decreased 36.1% (from 6.1℃ to 3.9℃) at 30 kW/m² and decreased 8.9% (from 6.7℃ to 6.1℃) at 90 kW/m² compared to the unrestricted single tube. As noted by Kang [8], the main reason for the decrease of ΔT_{sat} is because the intensity of liquid agitation by bubbles generated in the annuli is greater than in the single tube. However, the effect of the annuli on heat transfer gets decreased at relatively higher heat fluxes.

(2) Fig. 2(a) shows that the effects of annular space

on the nucleate boiling heat transfer for D =16.5 mm are very small. For example, ΔT_{sat} of S =5.0 mm decreases only 17.4% (from 4.6℃ to 3.8℃) compared to the single tube at the given heat flux (30 kW/m²). For D =25.4 mm, on the other hand, Fig. 2(c) shows that the effect of the annular space on nucleate boiling is significantly larger than that for the smaller tube diameter. According to Fig. 2(c), ΔT_{sat} decreases 60% (from 4.5℃ to 1.8℃) under the same heat flux used for D =16.5 mm. In summary, Fig. 2 shows that the larger diameter is more sensitive to the adoption of the revised annular space. The reason for this is partly because the number of bubbles on the tube surface increases more rapidly for the larger diameter. The bubbles generate more active liquid agitation, which increases heat transfer rate.

To examine the combined effect of tube diameter and gap size on nucleate pool boiling, h_b versus q'' data obtained for the tests of three different tube diameters are plotted in Fig. 3. It is particularly interesting to note that the difference between heat transfer coefficients for the annuli and the single tube at a given heat flux becomes larger as the gap size is small and the tube diameter is large. That is, when D =16.5 mm and S =5.0 mm only 18.1% (from 6.6 to 7.9 kW/m²-℃) increase in h_b is observed at 30 kW/m². At the same heat flux, more than 150% (from 6.7 to 17.0 kW/m²-℃) increase in h_b is obtained when D =25.4 mm and S =3.2 mm. When D =25.4 mm and q'' =30kW/m² 78.4% decrease in S (from 14.8 mm to 3.2 mm) results in more than 65% increase in h_b (from 10.3 to 17.0 kW/m²-℃). A similar tendency is also observed at higher heat fluxes.

The smaller gap results in better heat transfer at a given heat flux. The decrease in ΔT_{sat} and the increase in h_b are remarkable at relatively lower heat fluxes. This tendency is similar to the results of the annuli with closed bottoms [5]. The advantage of the present revised annuli is that no deterioration in the heat transfer coefficient is observed compared to a simple annulus, which has annular condition throughout the heated tube length. The deterioration is one of the negative characteristics when considering the adoption of the annuli with closed bottoms to the design of a heat exchanger. The revised annulus has still higher heat transfer coefficient than the single tube at lower heat fluxes and, moreover, has no deterioration in h_b at higher heat fluxes. Therefore, it can be suggested as an effective method to enhance pool boiling heat transfer of a heat exchanger, which consists of vertical tubes.

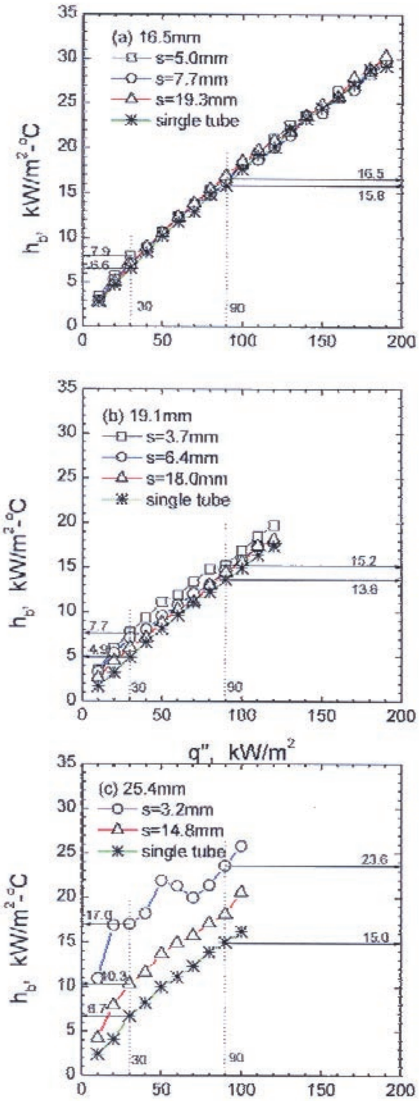

Fig. 3. Plots of h_b versus q'' data.

From visual observation (shown in Fig. 4) and a summary of the previous results [5,8] there seem to be two competing effects on the nucleate boiling heat transfer. One is the effect of liquid agitation by bubbles generated on the surface, which increases the heat transfer rate, and the other is the effect of bubble coalescence and the formation of large vapor slugs in the high heat flux region in particular, which reduces heat transfer from the tube surface. If the revised annulus, which has a shorter outer tube (L_o =0.2 m), is taken, no generation of large vapor slugs in the annular space is observed because the slugs, which de-

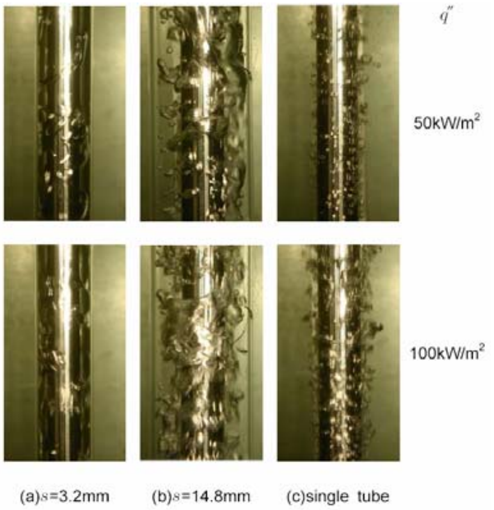

Fig. 4. Photos of pool boiling nearby thermocouple #5 (D =25.4mm).

crease the heat transfer rate, are generally forming nearby the upper region of the vertical tube.

Once a bubble is generated, it grows and is detached from the surface. The detached bubbles are moving along the tube surface to the upper flow exit of the annulus and coalescing with the relevant bubbles. The bubbles initially generate liquid agitation, which increases heat transfer. If the size of a bubble increases large enough to be squeezed in the annular space, its upward-flow is interrupted by the inlet flow. After all, heat transfer on the surface is decreased since liquid supply to the surface is not enough. The creation of the large bubbles is considered as the major cause of the heat transfer deterioration in the annuli with closed bottoms [5]. The location where the deterioration is initiated is the upper region of the annulus, as the annular gap size is small (see Fig. 5). The adoption of the shorter outer tube prevents the deterioration since the bubbles are not restricted in the small space around the upper region of the heated tube. Moreover, the pulsating flow in the annular space, which generates active liquid agitation, is still created in the revised annulus.

4. Conclusions

To suggest a way of enhancing pool boiling heat transfer on a vertical tube, the revised annuli with a shorter outer tube (L_o =0.2 m) have been studied. The length of the heated tube is 0.54 m. For the tests, water at atmospheric pressure and three tube diameters

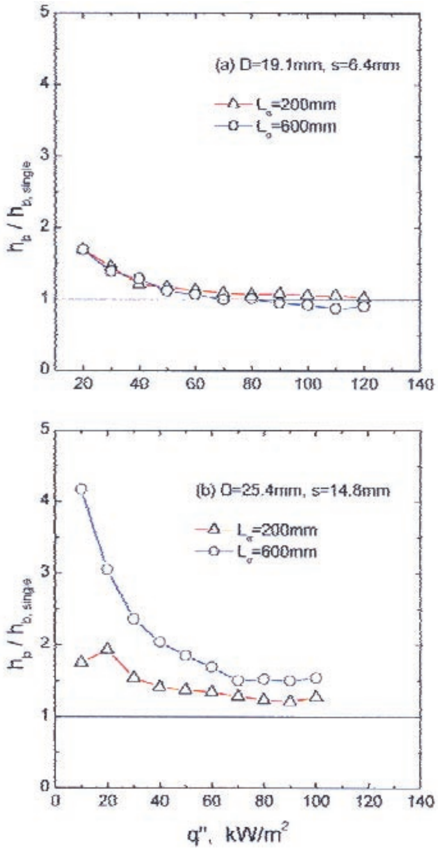

Fig. 5. Plots of $h_b / h_{b,\sin gle}$ versus q'' as L_o changes.

(16.5, 19.1, and 25.4 mm) have been used. To identify the increase in heat transfer, the results of the annuli have been compared to the unrestricted single tube. The revised annuli remarkably increase heat transfer on the surface compared to the unrestricted tube. When D =25.4 mm and S =3.2 mm, more than 150% (from 6.7 to 17.0 kW/m²-°C) increase in the heat transfer coefficient is observed at 30 kW/m² compared to the single unrestricted tube. Moreover, the revised annuli could remove the possibility of heat transfer degradation. The active liquid agitation and the prevention of the big bubble slugs formation are considered as the main reasons for the heat transfer increase and the removal of the heat transfer deterioration, respectively.

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