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Effects of Outflow Area on Saturated Pool Boiling in Vertical Annulus with Closed Bottoms

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1. Introduction

The mechanisms of pool boiling heat transfer have been studied extensively to design efficient heat transfer devices or to assure the integrity of safety related systems [1, 2]. However, knowledge on pool boiling heat transfer in a confined space is still quite limited [3]. The confined nucleate boiling is an effective technique to enhance heat transfer [4, 5].

Improved heat transfer might be attributed to an increase in the heat transfer coefficient due to vaporization from the thin liquid film on the heating surface or increased bubble activity [5, 6]. According to Cornwell and Houston, the bubbles sliding on the heated surface agitate environmental liquid [7]. 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 [8]. The increase in the intensity of liquid agitation results in heat transfer enhancement.

Sometimes a deterioration of heat transfer appears at high heat fluxes for confined boiling [6, 9]. The cause of the deterioration is suggested as active bubble coalescence [8]. Recently, Kang [3] published inflow effects on pool boiling heat transfer in a vertical annulus with closed bottoms. Kang [3] regulated the gap size at the upper regions of the annulus and identified that effects of the reduced gaps on heat transfer become evident as the heat flux increases. This kind of geometry is found in an in-pile test section [10].

Since more detailed analysis is necessary, effects of the outflow area on nucleate pool boiling heat transfer are investigated in this study. Up to the author's knowledge, no previous results concerning to this effect have been published yet.

2. Experiments

For the tests, the assembled test section (Fig. 1) is located in a water tank which has a rectangular cross section (950×1300 mm) and a height of 1400 mm. The heat exchanging tube is a resistance heater made of a very smooth stainless steel tube.

The tube outside 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 that 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 are used.

Table 1. Values of the Area Ratios

d, mm	A_{out}, mm^2	$A_r=A_{out}/A_{gap}$
10	78.5	0.04
15	176.6	0.08
20	314.0	0.15
25	490.6	0.23
30	706.5	0.33
38	1133.5	0.53
55.4	2409.3	1.13

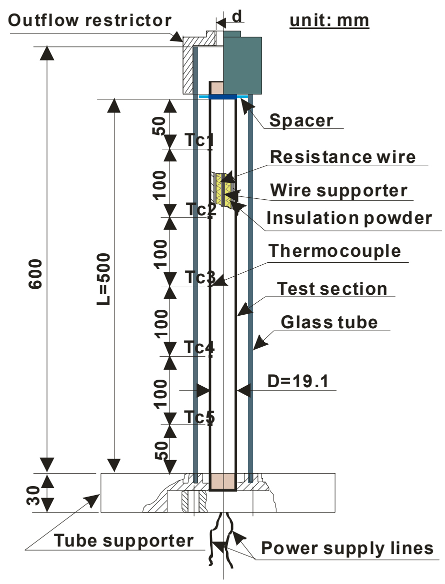

Fig. 1. Schematic diagram of the assembled annulus.

The gap size of the main body of the annulus is 18.2 mm. The upside outflow from the annular space is controlled by the flow restrictor as listed in Table 1. The area ratio (A_r) is defined as the outflow area (A_{out}) divided by the cross sectional area (A_{gap}) of the annulus.

The temperatures of the tube surfaces are measured when they are at steady state while controlling the heat flux on the tube surface with input power. The uncertainties of the experimental data are calculated from the law of error propagation [11]. The 95 percent confidence uncertainty of the measured temperature has the value of ±0.11 °C. The uncertainty of the heat flux is estimated to be ± 0.7%. After calculation and taking the mean of the uncertainties of the propagation errors the uncertainty of the heat transfer coefficient (h_b) can be decided as ± 6%.

3. Results

Figure 2 shows variations in heat transfer coefficients for the three heat fluxes of 30, 50, and 100 kW/m^2 as A_r changes. There are only slight changes in heat transfer coefficients when A_r is greater than 0.53. The decrease in A_r less than 0.53 ultimately leads to the decrease in heat transfer. The tendency is same regardless of the heat flux.

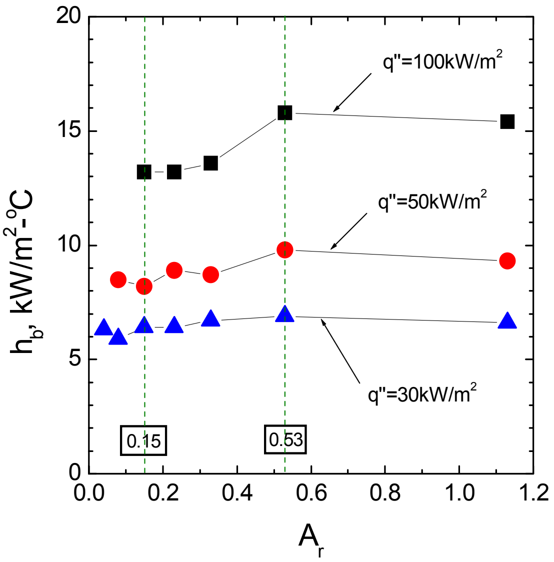

Fig. 2. Variations in heat transfer coefficients as A_r changes.

When 0.53< A_r , the generated bubbles exit the outlet relatively freely. However, because of the outflow restrictor big bubble bunches were generated in the space under the restrictor. The size of the bubble lump is increasing until the amount of the buoyancy is enough to escape from the annulus. If the lump flows out, a sudden rush of the liquid is occurred. During the process the inside fluid is accelerated to move up and downward, generating a pulsating flow, in the gap space. As a result very active liquid agitation is observed visually. The high rate of heat transfer by boiling in the gap space has been ascribed to the intense agitation of the liquid and this is the major cause of heat transfer enhancement.

More decrease in A_r increases the resistance between the restrictor and the outflow. As Kang [3] explained the major causes of the deterioration are the formation of large bubble slugs around the tube surface. If big size bubble lumps were generated, the intensity of liquid agitation should be decreased. The lumps prevent the smooth supply of liquid into the gap space. Thereafter the decrease in heat transfer is caused.

As the area ratio decreases less than 0.15 the heat transfer coefficient increases slightly. The enhancement in heat transfer is ascribed to the evaporative mechanism under the elongated bubble. As A_r decreases the size of the coalesced bubble gets increased. The bubbles were, in turn, squeezed in the gap space and the elongated bubbles covered the tube surface. The thickness of the liquid film under the bubble was rapidly decreased. The thin liquid film decreases thermal resistance between the tube surface and the bubble. Then, liquid evaporates actively to the inside of the bubble and results in a sudden increase in heat transfer.

4. Conclusions

The outflow area of a vertical annulus with closed bottoms was varied to investigate its effect on pool boiling heat transfer. For the test, a smooth stainless steel tube of 19.1 mm diameter and the water at atmospheric pressure were used. The ratio of areas of the outflow and the gap space was varied between 0.04 and 1.13. As the area ratio decreased a clear change in heat transfer was observed at high heat fluxes. It was found that heat transfer on the tube surface was strongly dependent on the intensity of the liquid agitation and the evaporative mechanism under the coalesced bubbles. As the ratio was lower than 0.1 the generation of critical heat flux was observed even at a low heat flux less than 100kW/m^2.

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