Saturated Pool Boiling in Vertical Annulus with Reduced Outflow Area

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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

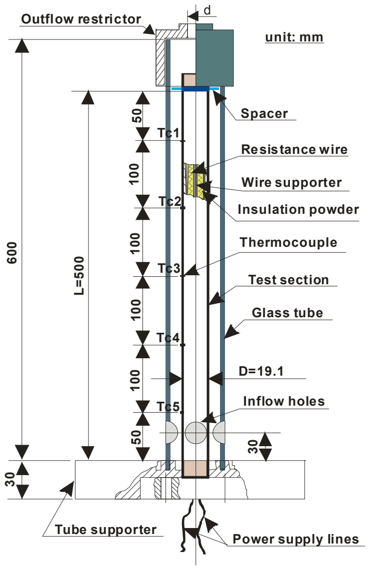

Fig. 1. Schematic diagram of the assembled annulus.

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 as A_r changes. Throughout the heat fluxes (q'') three obvious tendencies are observed. For $0.04 \le A_r \le 0.15$, h_b increases. As the area ratio increases from 0.15 to 0.33, a gradual decrease in the heat transfer coefficients is observed. More increase in A_r also increases h_b. As the gap ratio is more than 0.53, however, no clear change in the heat transfer coefficient is observed. Those tendencies are same regardless of the heat flux.

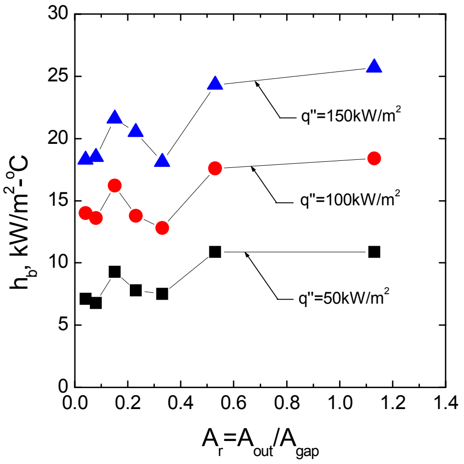

Fig. 2. Variations in heat transfer coefficients as A_r changes.

As the area ratio decreases from 1.13 to 0.33 the flow rate in the annular space decreases. The amount of convective heat transfer (especially, at the lowermost regions) and the intensity of liquid agitation along the space gets decreased due to the reduced fluid velocity. The heat transfer coefficients are very sensitive to the convective flow around the lower regions. More decrease in A_r from 0.33 to 0.15 reduces the flow velocity and accelerates the rate of bubble coalescence. The small outflow area obstructs the outward bubble flow from the annulus. Then, the detached bubbles coming from the lower part of the tube get stagnant for a while and accumulate at the upper region of the annulus. During the stay the bubbles are coalescing together and are growing to a big lump of bubble. Thereafter, the upward rising velocity of the fluid gets decreased because of the lump. The size of the bubble lump is increasing until the amount of the buoyancy is enough to escape from the gap space. If the lump flows out a vacancy is created in the gap space. Then, 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 at the heating surface by the bubbles and this is the major cause of heat transfer enhancement. As the area ratio gets decreased lower than 0.15 the creation of the bigger bubbles is accelerated even at a low heat fluxes. If big size bubble lumps were generated, the intensity of the liquid agitation should be decreased since the length for the flow acceleration is shorten. Moreover, the lumps prevent the smooth supply of liquid into the gap space. Thereafter the decrease in the heat transfer rate is caused.

4. Conclusions

The outflow area has been varied to investigate its effect on pool boiling heat transfer in a vertical annular space. For the test, a smooth stainless tube of 19.1 mm diameter and the water at atmospheric pressure have been used. The ratio of areas of the outflow and the gap space has been changed from 0.04 to 1.13. As the area ratio decreases an obvious change in heat transfer is observed. The major cause for the tendency is attributed to the formation of a lumped bubble around the upper regions of the annulus and the reduced flow rate.

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