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Pool boiling heat transfer on the tube surface in an inclined annulus

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A B S T R A C T

An experimental study was carried out to investigate the pool boiling heat transfer in an inclined annular tube submerged in a pool of saturated water at atmospheric pressure. The outer diameter and the length of the heated inner tube were 25.4 mm and 500 mm, respectively. The gap size of the annulus was 15 mm. For the tests, annuli with both open and closed bottoms were considered. The inclination angle was varied from the horizontal position to the vertical position. At a given heat flux, the heat transfer coefficient was increased with the inclination angle increase. Effects of the inclination angle on heat transfer were more clearly observed in the annulus with open bottoms. The main cause for the tendencies was considered as the difference in the intensity of liquid agitation and bubble coalescence due to the enclosure by the outer tube. One of the important factors in the annulus with open bottom was the convective fluid flow.

1. Introduction

One of the interest issues in heat transfer should be pool boiling. Since the subject is of importance in fluid flow and heat transfer, the mechanisms of pool boiling have been studied extensively for the several decades [1]. Recently, it has been widely investigated in nuclear power plants for application to the design of new passive heat removal systems employed in the advanced light water reactors designs [2]. Through the review on the published results it can be concluded that two of the efficient ways to increase the heat transfer rate are considering a confined space and an inclined surface. The effects of surface orientation and gap size (s) on the pool boiling heat transfer have received increased attention. Two practical approaches have been employed to obtain effects of the inclination angle (θ) on pool boiling heat transfer for the heated surface as follows: (1) the inclination angles itself and (2) combined effects with a confinement.

Stralen and Sluyter [3] performed a test to find out boiling curves for platinum wires in the horizontal and vertical position at atmospheric pressure. They concluded that the horizontal type was more effective than the vertical type both in the natural convection and boiling regions. The major cause of the reduction in heat transfer for the vertical position is due to the formation of large vapor slugs. The coalesced bubbles are distributed over the entire heating surface for a vertical wire and this behavior differs from that for a horizontal wire, where bubble coalescence is generally restricted to nearby nuclei.

Githinji and Sabersky [4] reported interesting results related with the inclination angle of a plate like a narrow strip. They changed the orientation from horizontally facing upward, to vertical, and to horizontally facing downward. They observed the importance of the gravity on pool boiling heat transfer. For the surface facing downward heat transfer coefficients (h_b) decrease much as the heat flux (q'') increases due to the bubbles coalesced on the surface.

Nishikawa et al. [5] studied heat flux and wall superheat (ΔT_{sat}) on a flat plate oriented at an angle, that varied from a horizontal, upward-facing position to the near-vertical position in the water. According to them, the effect of the surface configuration is remarkable at low heat fluxes and the heat transfer coefficient increases as the inclination angle is increased in this case, while no marked effect is observed at high heat fluxes. One year later, Lienhard [6] explained the loss of orientation dependence at higher heat fluxes using the Moissis–Rerenson transition.

Jung et al. [7] performed some experiments for inclined plates and R-11. For all surfaces investigated, the superheat decreases by 15–25% as the inclination angle changes in the relatively low heat flux range (i.e., 10–40 kW/m^2). Beyond this heat flux range, however, the superheat remains constant regardless of the surface orientation. Fujita et al. [8] studied the combined effects of inclination angle and gap size between two plates. According to the outputs, the effect of the inclination angle is closely related with the gap size. Decreasing the gap size much narrower (0.15 mm for the case) the boiling behavior does not change with the inclination angle.

Although some authors have studied effects of the inclination angle on pool boiling heat transfer along with the effects of

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Nomenclature

A	empirical constant	n	constant
A_T	data acquisition error, °C	P_T	precision limit, °C
B	empirical constant	q''	heat flux, W/m^2
C	empirical constant	T_{sat}	saturation temperature, °C
D	diameter of the heating tube, m	T_W	tube wall temperature, °C
h_b	boiling heat transfer coefficient, W/m^2 °C	V	supplied voltage, V
I	supplied current, A	ΔT_{sat}	tube wall superheat (=T_W–T_{sat}), °C
k	constant	θ	inclination angle, deg or rad
L	heated tube length, m		

geometry, pressure, and surface conditions, no detailed studies have been performed for tubes until Chun and Kang [2] studied the effect of tube orientation on pool boiling heat transfer in combination with tube surface roughness. According to Chun and Kang [2], the slope of q'' versus ΔT_{sat} curve of the vertical tube becomes smaller than that of the horizontal tube as the surface roughness decreases. The results obtained by Kang [9] at three inclination angles (0°, 45°, and 90°) have a large effect on pool boiling heat transfer. The effect of inclination angle is more strongly observed in the smooth tube and if a tube is properly inclined (θ = 45° for the case) enhanced heat transfer is expected in comparison with the horizontal and the vertical positions. Some more detailed study for the inclination angle has performed by Kang [10] considering different tube diameters and inclination angles.

Recently, Narayan et al. [11] studied the effect of nanoparticles, suspended in pure liquids, on nucleate pool boiling heat transfer at various surface orientations. They conducted systematic experiments on smooth tube of diameter 33 mm and length 170 mm at various inclinations (0°, 45°, and 90°). Horizontal orientation gave maximum heat transfer and the heating surface, when inclined at 45°, gave minimum heat transfer. Parker and El-Genk [12] investigated effects of orientation of porous graphite and smooth copper surfaces on saturation nucleate boiling and critical heat flux of FC-72. Sateesh et al. [13] conducted experiments to study the effect of tube inclination on nucleate pool boiling heat transfer for different tube diameters and surface roughness values. Water, ethanol, and acetone at atmospheric were used for the experiment. As the angle of inclination was reduced from 90° with horizontal, the top wall temperature was found to increase and the bottom wall temperature was found to decrease.

Effects of the inclination angle on the critical heat flux also have been studied for the geometries of plates, tubes, and confined spaces [14–19]. According to the published results, it is obvious that the critical heat flux depends on the inclination angle much. However, the amount of the inclination angle on the critical heat flux is closely related with the geometric parameters (i.e., gap size).

Summarizing the published results, it can be said that effects of the inclination angle on pool boiling heat transfer closely depend on the heating surface geometry. As Cornwell and Houston [20] suggested nucleate boiling on a tube differs considerably from that on a flat plate. The same is true for the wire. One of the important parameters in pool boiling is the gap size. As Fujita et al. [8] already observed the gap size can change the tendency of heat transfer on an inclined surface. Therefore, the annular space in combination with the inclination angle can be a good design parameter to be investigated. Up to the author's knowledge, no previous results concerning this effect have been published yet, except the author's previous study [21]. Kang [21] investigated pool boiling in an inclined annulus of 12.5 mm gap with open bottoms. Kang [21] conducted tests for the four inclination angles (45°, 75°, 60°, and 90°) and concluded that there existed much difference between the results for the single tube and the annulus. Therefore, the present study aims to extend Kang's previous results [21] to the different tube diameter, gap size, and confinement condition, which can provide a clue to the thermal design of those kinds of facilities.

2. Experiments

A schematic view of the present experimental apparatus and an assembled test section is shown in Fig. 1. The water tank (Fig. 1a) was made of stainless steel and had a rectangular cross section (9501300 mm) and a height of 1400 mm. The sizes of the inner tank were 80010001100 mm (depthwidthheight). Four auxiliary heaters (5 kW/heater) were installed at the space between the inside and outside tank bottoms. The heat exchanging tube was simulated by a resistance heater (Fig. 1b) made of a very smooth stainless steel tube (tube diameter D = 25.4 mm and the heated length L = 500 mm). The surface of the tube was finished through a buffing process to have a smooth surface. Electric power of 220 V AC was supplied through the bottom side of the tube.

The tube outside was instrumented with five T-type sheathed thermocouples (diameter was 1.5 mm). The thermocouple tip (about 10 mm) was brazed on the tube wall. The brazing metal was a kind of brass and the averaged brazing thickness was less than 0.1 mm. The temperature decrease along the brazing metal was calibrated by the one dimensional conduction equation. The water temperatures were measured with six sheathed T-type thermocouples brazed on a stainless steel tube that was placed vertically at a corner of the inside tank. All thermocouples were calibrated at a saturation value (100°C since all tests were done at atmospheric pressure). To measure and/or control the supplied voltage and current, two power supply systems were used. The capacity of each channel was 10 kW. For the tests, the heat exchanging tube was assembled vertically at the supporter (Fig. 1a) and an auxiliary tube supporter was used to fix a glass tube (Fig. 1b). To make the annular condition, a glass tube of 55.4 mm inner diameter and 600 mm length were used. Accordingly, the annular gap size was 15 mm. For the tests of the annulus with closed bottoms, a glass tube without the bottom inflow holes were used. The inclination angle is measured from the horizontal position as depicted in Fig. 1a.

After the water tank was filled with water until the initial water level reached 1100 mm, the water was then heated using four preheaters at constant power. When the water temperature was reached the saturation value, the water was then boiled for 30 min to remove the dissolved air. The temperatures of the tube surfaces (T_W) were measured when they were at steady state while the heat flux on the tube surface was controlled with input power.

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

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