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Local Pool Boiling Heat Transfer on a 3-Degree Inclined Tube Surface

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1. Introduction

Mechanisms of pool boiling heat transfer have been studied for a long time. Recently, it has been widely investigated in nuclear power plants for the purpose of acquiring inherent safety functions in case of no power supply [1]. To design more efficient heat exchangers, effects of several parameters on heat transfer must be studied in detail. One of the major issues is variation in local heat transfer coefficients on a tube.

Lance and Myers [2] reported that the type of boiling liquid can change the trend of local heat transfer coefficients along the tube periphery. Lance and Myers said that as the liquid is methanol the maximum local heat transfer coefficient was observed at the tube bottom while the maximum was at the tube sides as the boiling liquid was n-hexane. Cornwell and Einarsson [3] reported that the maximum local heat transfer coefficient was observed at the tube bottom, as the boiling liquid was R113. Cornwell and Houston [4] explained the reason of the difference in local heat transfer coefficients along the tube circumference with introducing effects of sliding bubbles on heat transfer.

According to Gupta et al. [5], the maximum and the minimum local heat transfer coefficients were observed at the bottom and top regions of the tube circumference, respectively, using a tube bundle and water. Kang [6] also reported the similar results using a single horizontal tube and water [6]. However, the maximum heat transfer coefficient was observed at the angle of 45 deg. Sateesh et al. [7] investigated variations in local heat transfer coefficients along a tube periphery as the inclination angle was changed.

Summarizing the published results, some parts are still remaining to be investigated in detail. Although pool boiling analysis on a nearly horizontal tube is necessary for the design of the advanced power reactor plus [8], no previous results are published yet. Therefore, the present study is aimed to study variations in local pool boiling heat transfer coefficients for a 3-degree inclined tube submerged in subcooled or saturated water.

2. Experiments

For the tests, the assembled test section (Fig. 1) was 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 azimuthal angle (θ) was regulated by rotating the flange. The local values were determined at every 45 deg from the very bottom to the uppermost of the tube periphery.

The tube outside was instrumented with five T-type sheathed thermocouples. The thermocouple was brazed on the tube wall. The water temperatures were measured with six sheathed T-type thermocouples that placed vertically at a corner of the inside tank. All thermocouples were 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 were used.

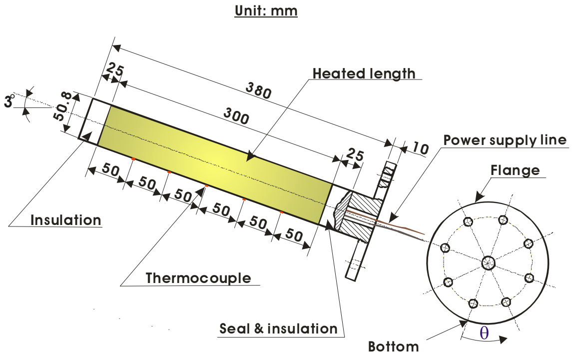

Fig. 1. Schematic diagram of the test section.

The temperatures of the tube surfaces were 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 were calculated from the law of error propagation [9]. 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 the local heat transfer coefficients as the degree of subcooling changes when the heat flux is 20 kW/m^2. The local coefficient is the maximum as the azimuthal angle is 45 deg and, then, it decreases, as the angle is 45 deg. The major cause of the increase in heat transfer coefficients is liquid agitation due to rising bubbles. As a bubble moves along the tube periphery, it agitates relevant liquid. Moreover, since some amount of space is generated as the bubble departs, liquid rushes to the space. At $\theta=45$

deg, the intensity of liquid agitation seems to have its largest value, since enough moving bubbles are observing and the region is relatively free from the bubble coalescence.

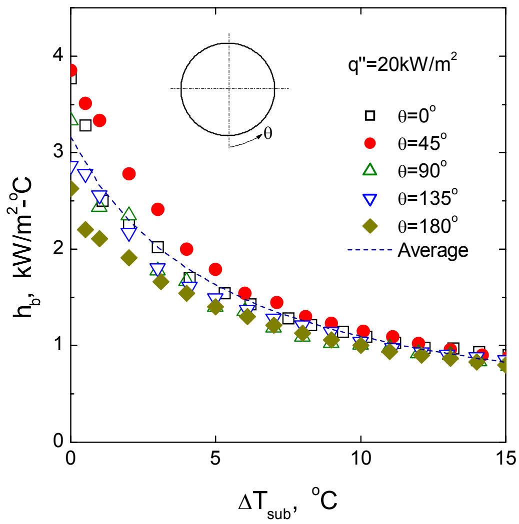

Fig. 2. Variations in local heat transfer as ΔT_{sub} changes.

As the azimuthal angle is 90 deg, bubbles that came from the lower side start to depart from the surface due to buoyancy, and the intensity of liquid agitation decreases. This generates a big bunches of bubbles on the surface. The coalesced bubbles prevent easy access of relevant liquid to the heated surface and decrease the heat transfer rate at the upper regions of the tube. The angle of the largest heat transfer coefficient was decided as the location where the effect of liquid agitation was high and the effect of bubble coalescence was low. Therefore, it can be moved to other locations since these two mechanisms depend on the heat flux for the present case. A greater supply of electric power could move the angle to the tube bottom due to the growth of the bubble coalescence region.

As the degree of water subcooling (ΔT_{sub}) decreases the size and the movement of bubbles are increasing. Then, the intensity of liquid agitation gets increased due to the sliding bubbles. The difference along the local heat transfer coefficients increases as ΔT_{sub} increases. There is about 60 percent difference between the maximum and the minimum local heat transfer coefficients at ΔT_{sub}=0.5 °C.

To predict the local heat transfer coefficients, an empirical correlation has been suggested by using the least-squares method and experimental data. The empirical correlation can be correlated as a function of the heat flux and the subcooling as follows:

$$h_b = \frac{1}{\left(\frac{C_1 \ln q''}{q''^{C_2}}\right)\Delta T_{sub} + \frac{C_3 \ln q''}{q''^{C_4}}} \tag{1}$$

The values of the empirical constants are listed in Table 1. The developed correlation can predict the measured experimental data within ±10% error bound. Therefore, it can be said that the suggested correlation could predict the experimental data very well.

Table 1. Values of the empirical constants

θ	C_1	C_2	C_3	C_4
0°	0.94	1.29	3.01	1.15
45°	0.84	1.26	2.37	1.11
90°	1.41	1.39	4.73	1.27
135°	1.15	1.37	6.77	1.36
180°	0.96	1.32	7.91	1.35
Avg.	1.06	1.33	4.96	1.25

4. Conclusions

Changes in local pool boiling heat transfer coefficients on the outside surface of a 50.8 mm diameter tube of 3-degree inclination angle tube have been investigated experimentally. Both subcooled and saturated water at atmospheric pressure are studied. The azimuthal angle for the maximum and the minimum local coefficients are dependent on the degree of subcooling and the heat flux. The major mechanisms affecting heat transfer on the surface arre liquid agitation and bubble coalescence.

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