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Local Pool Boiling Heat Transfer Coefficients on Near Horizontal Tubes

Myeong-Gie Kang*
Department of Mechanical Engineering Education, Andong National University
388 Songchun-dong, Andong-city, Kyungbuk 760-749
**Corresponding author: mgkang@andong.ac.kr*

1. Introduction

Mechanisms of pool boiling have been widely investigated in nuclear power plants for the purpose of acquiring inherent safety functions in case of no power supply [1, 2]. One of the major issues is variation in local heat transfer coefficients on a tube.

Lance and Myers [3] reported that the type of boiling liquid can change the trend of local heat transfer coefficients (h_b) along the tube periphery. They said that as the liquid is methanol the maximum local heat transfer coefficient ($h_{b,\max}$) was observed at the tube bottom while the maximum was at the tube sides as the boiling liquid was n-hexane. Cornwell and Einarsson [4] reported that $h_{b,\max}$ was observed at the tube bottom, as the boiling liquid was R113. Cornwell and Houston [5] 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. [6], 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 [7] also reported the similar results using a single horizontal tube and water. However, the maximum heat transfer coefficient was observed at the angle of 45°.

Sateesh et al. [8] studied variations of h_b along the tube periphery while controlling the inclination angle (ϕ). They tested five inclination angles (i.e., ϕ=0°, 30°, 45°, 60°, and 90°). The top wall superheat increases and bottom wall superheat decreases as the inclination is changed 90° to 0° from the horizontal. The cause for the tendency is thought as the bubble sliding length.

Recently, Kang et al. [2] studied pool boiling heat transfer on a 3-deg inclined tube for application to the design of the advanced power reactor plus. Since some more data is necessary, the present study is aimed to study variations in local pool boiling heat transfer coefficients on nearly horizontal tubes.

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. They 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.

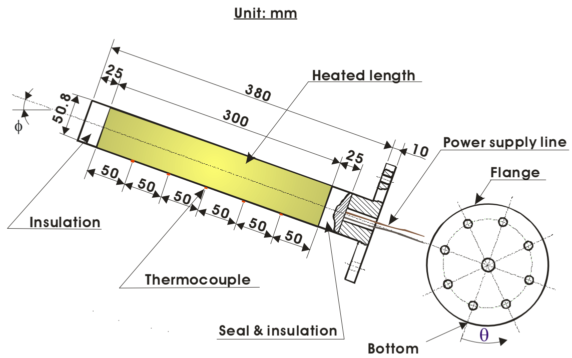

Fig. 1. Schematic diagram of the test section.

The temperatures of the tube surfaces were measured when they are at steady state while controlling the heat flux on the tube surface. 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 are decided as ± 6%.

3. Results

Figure 2 shows peripheral distribution of h_b as the azimuthal angle varies for the heat fluxes of 10 and 100 kW/m^2. To investigate the variation of h_b the angle of the tube inclination was changed from the horizontal (ϕ=0°) to 9°.

The overall distribution of h_b depends on both of the heat flux and the inclination angle. At q''=10kW/m^2, $h_{b,\max}$ is observed at θ=45° as the inclination angles of the tube are 0°, 3°, and 6°. The more increase of the inclination angle to 9° changes the azimuthal angle for $h_{b,\max}$ to be θ=0°. As the heat flux increases to 100 kW/m^2, $h_{b,\max}$ is observed at θ=0° for the inclination angles of 0°, 3°, and 6°. The increase of the heat flux moves the azimuthal angle for $h_{b,\max}$ from 45° to 0°. Throughout the heat fluxes tested the azimuthal angle $h_{b,\max}$ is not changed and has the value of θ=45° as the tube is in horizontal position. Although the azimuthal angle for $h_{b,\max}$ is changed depending on the heat flux and the inclination angle, the azimuthal angle for the minimum heat transfer coefficient is remained unchanged due to ϕ and q'' and has the value of 180°.

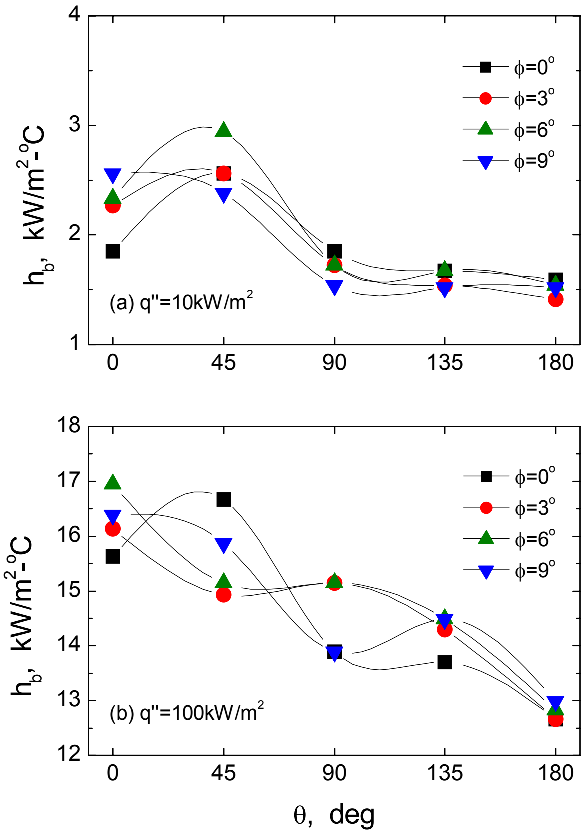

Fig. 2. Peripheral h_b distribution.

The azimuthal angle for $h_{b,\max}$ is decided as the location where the effects of liquid agitation and bubble coalescence are high and low, respectively. Therefore, it can be moved to the other location since these two mechanisms are dependent on the inclination angle and the heat flux. As shown in Fig. 2 the increases in heat flux and inclination angle move the azimuthal angle for the maximum heat transfer coefficient to the bottom side of the tube.

As the tube is inclined from the horizontal position, the sliding lengths of bubbles along the tube periphery are increased. The sliding length increases in proportion to $1/\cos\phi$. The bubbles generated at the bottom side of the inclined tube are, then, slightly moves along the bottom regions. Throughout the movement it agitates relevant liquid and becomes the major reason of heat transfer enhancement at the lowermost position.

Although the local heat transfer coefficient changes depending on the inclination angle, the average heat transfer coefficient ($h_{b,avg}$) along the tube periphery is almost same and can be correlated as a function of the heat flux as follows:

$$h_{b,avg} = 0.218 q''^{0.912} \quad (1)$$

The dimensions for $h_{b,avg}$ and q'' are kW/m²-ºC and kW/m², respectively. The developed correlation can predict the measured experimental data within ±2% error bound.

4. Conclusions

Effects of the inclination angle on the changes of local pool boiling heat transfer coefficients on the outside surface of a 50.8 mm diameter tube have been investigated experimentally in the saturated water at atmospheric pressure. The azimuthal angles for the maximum and the minimum local coefficients are dependent on the inclination angle and the heat flux. The major mechanisms changing heat transfer on the surface are liquid agitation and bubble coalescence.

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