Transactions of the Korean Nuclear Society Spring Meeting
Jeju, Korea, May 29-30, 2014

Effects of Elevation Angle on Pool Boiling Heat Transfer on Tandem Tubes

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1. Introduction

The mechanism of pool boiling heat transfer has been studied extensively in the past since it is closely related with the thermal design of more efficient heat exchangers. One of the major issues is the bundle effect, which is defined as the ratio of the heat transfer coefficient (h_b) for an upper tube in a bundle with lower tubes activated to that for the same tube activated alone in the bundle [1]. Most studies were focused on the bundles consisting of many tubes for application to a flooded evaporator [2-4].

Along with the tube spacing, its location is also of interest. Many researchers have been investigated the effect of tube spacing on heat transfer for the tube bundles [4-6] and the tandem tubes [7,8]. The heat transfer on the upper tube of the tubes is enhanced compared with the single tube [8]. However, the maximum heat transfer coefficient of the upper tube decreases [7], increases [8], or negligible [5] with increasing tube pitch in pool boiling.

The effect of tube array on heat transfer enhancement was also studied for application to the flooded evaporators [9,10]. The upper tube within a tube bundle can significantly increase nucleate boiling heat transfer compared to the lower tubes at moderate heat fluxes. At high heat fluxes these influences disappear and the data merge onto the pool boiling curve of a single tube [11].

Since the source of the convective flow in pool boiling is the lower heated tube, the heat flux of the lower tube (q_L'') is of interest. The only useful study is by Ustinov et al. [12]. They investigated effects of the heat flux of lower tube on pool boiling of the upper tube. They used microstructure and identified that the increase in the heat flux of lower tube decreased the superheat (ΔT_{sat}) of the upper tube.

Summarizing the previous results it can be stated that heat transfer coefficients are highly dependent on the tube geometry and the heat flux of the lower tube. Therefore, the present study is focused on the effects of an elevation angle (θ) of the tubes and the heat flux of the lower tube on pool boiling heat transfer on tandem tubes. To the present author's knowledge, no results on this effect have as yet been published.

2. Experiments

For the tests, the assembled test section was located in a water tank which had a rectangular cross section (950×1300 mm) and a height of 1400 mm as shown in Fig. 1. The heat exchanging tube is a resistance heater made of a very smooth stainless steel tube of 19 mm outside diameter (D) and 400 mm heated length. The tube pitch (P) was 28.5 mm. The elevation angle (shown in Fig. 2) of the tubes was changed every 15° from the horizontal position to 90°. The heat flux of the lower tube was (1) set a fixed values of 0, 30, 60, and 90 kW/m^2 or (2) varied equal to the heat flux of the upper tube (q_T'').

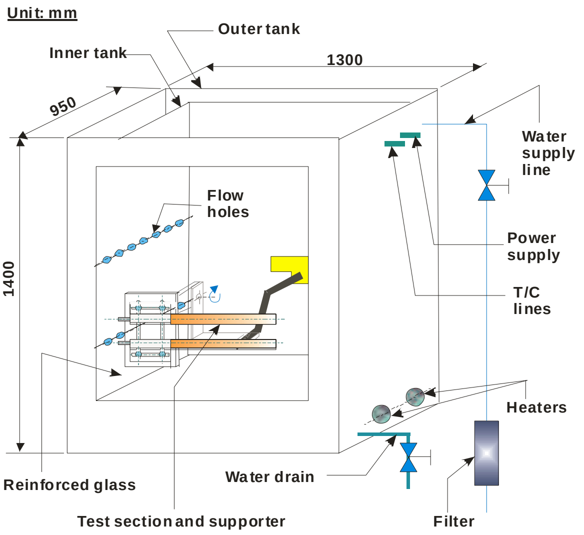

Fig. 1. Schematic of experimental apparatus.

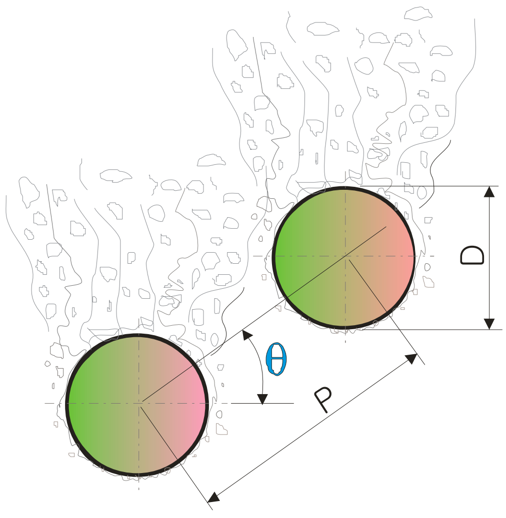

Fig. 2. Elevation angle and pitch of tandem tubes.

The water tank was filled with water until the initial water level reached 1100 mm, the water was then heated using four pre-heaters at constant power. When the water temperature was reached the saturation value, the water was then boiled for 30 minutes to remove the dissolved air. The tube outside was instrumented with six T-type sheathed thermocouples brazed on the tube wall. The water temperatures were measured with six sheathed thermocouples. 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, power supply systems were used.

The uncertainties of the experimental data were calculated from the law of error propagation [13]. The 95 percent confidence uncertainty of the measured temperature has the value of ±0.11 °C. The uncertainty in the heat flux was estimated to be ±0.7%. Since the values of the heat transfer coefficient were the results of the calculation of $q_T''/\Delta T_{sat}$, a statistical analysis on the results was performed. After calculating and taking the mean of the uncertainties of the propagation errors, the uncertainty of the heat transfer coefficient was determined to be ±6%.

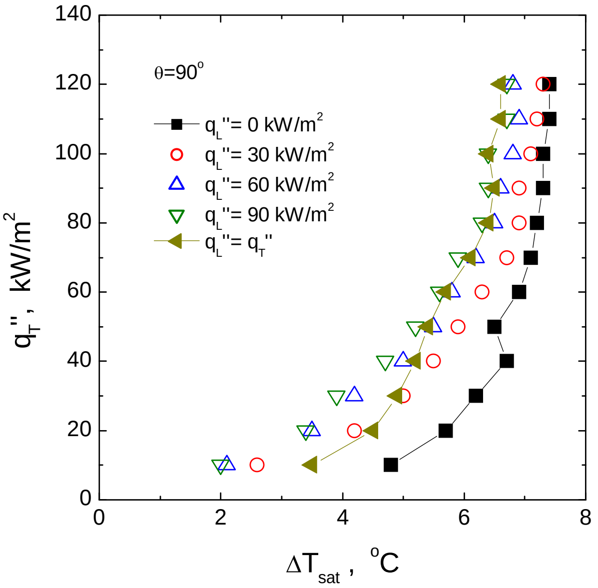

Fig. 3. Plots of q_T'' versus ΔT_{sat} at θ =90°.

3. Results

Figure 3 shows plots of q_T'' versus ΔT_{sat} data obtained from the experiments. The heat flux of the lower tube was changed for the elevation angle of 90°. As shown in the figure the heat transfer on the upper tube of the tubes is enhanced compared with the single tube (i.e., q_L'' =0 kW/m^2). The change of q_L'' from 0 to 90 kW/m^2 results in 37.1% (from 6.2 to 3.9°C) decrease of ΔT_{sat} when q_T'' =30kW/m². The gradual increase in q_L'' results in the decrease in ΔT_{sat} for the given heat flux. Throughout the heat fluxes tested the enhancement in heat transfer is much clearly observed at low or moderate heat fluxes.

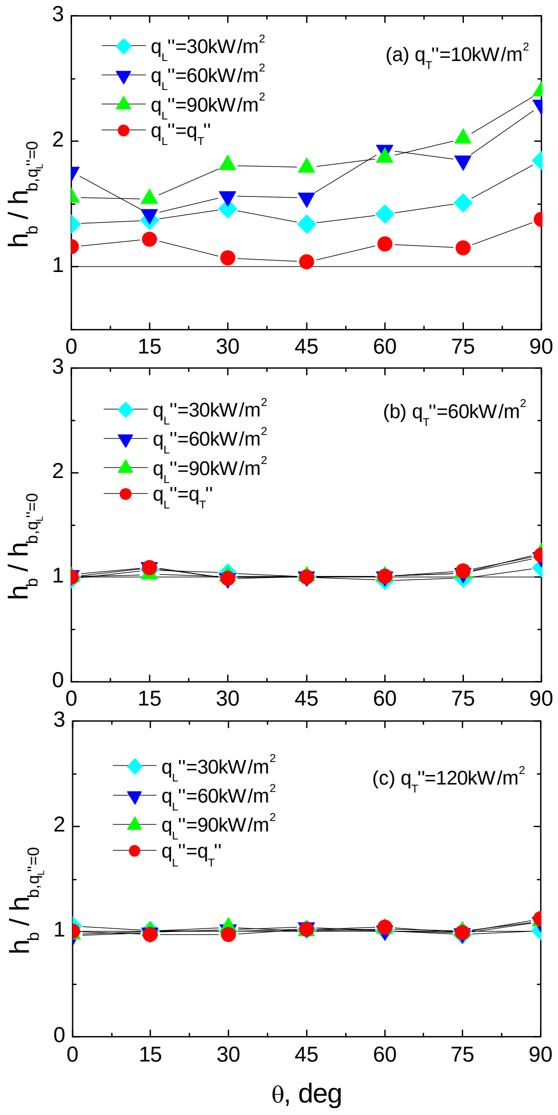

Fig. 4. Variations of bundle effect with θ and q_L'' .

To identify the bundle effect the ratios of $h_b/h_{b,q_L''=0}$ were obtained for the different q_L'' as the elevation angle changes from 0° to 90°. Results for the three q_T'' are shown in Fig. 4. The increase of both q_L'' and θ results in heat transfer enhancement. The bundle effect is clearly observed when $q_L'' > q_T''$ and q_T'' is at low heat fluxes. As the heat flux of the upper tube increases, the bundle effect decreases dramatically. The maximum bundle effect is observed at q_T'' =10 kW/m^2 and θ =90°. When the elevation angle increases the effects of the convective flow of liquid and bubbles from the lower tube get decreased. This decreases the bundle effect.

The bundle effect is expected as the convective onflow of bubbles and liquid, rising from the lower tube, enhances the heat transfer on the upper tube [8]. When the upper tube is at low heat flux a convection-controlled regime prevails. Therefore, the turbulent flow generated by the departed bubbles from the lower tube enhances heat transfer much. However, as the heat flux of the upper tube increases, the portion of the liquid convection gets decreased and, accordingly, the enhancement in heat transfer gets disappeared.

4. Conclusions

The effects of the elevation angle and the heat flux of the lower tube on the bundle effect were studied using the tandem tubes submerged in the water at atmospheric pressure. The increase of both $q_L^{''}$ and θ results in heat transfer enhancement. The bundle effect is clearly observed when $q_L^{''} > q_T^{''}$ and $q_T^{''}$ is at low heat fluxes.

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