Effects of Inclination Angle on Pool Boiling Heat Transfer from Tandem Tubes

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1. Introduction

The mechanism of pool boiling heat transfer has been studied extensively for the several decades since it is closely related to the design of passive type heat exchangers, which have been investigated in nuclear power plants to meet safety functions in case of no power supply [1]. Since the space for a heat exchanger install is usually limited, the exact estimation of the heat transfer is very important to keep up reactor integrity. One of the major issues in the design of a heat exchanger is the heat transfer in a tube bundle.

The heat transfer on the upper tube is enhanced compared with the single tube [2]. The enhancement of the heat transfer on the upper tube is estimated by the bundle effect (h_r). It 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. The upper tube within a tube bundle can significantly increase nucleated boiling heat transfer compared to the lower tubes at moderate heat fluxes. At high heat fluxes these influences disappear and the data merge the pool boiling curve of a single tube. It was explained that the major influencing factor is the convective effects due to the fluid velocity and the rising bubbles [3].

Along with the tube spacing, its location is also of interest. Kang [2] investigated that the bundle effect was dependent on the tube pitch, elevation angle, and the heat flux of the lower tube (q''_L). The bundle effect was clearly observed when q''_L was greater than the heat flux of the upper tube (q''_T). The bundle effect was increased when the pitch was decreased and the elevation angle was increased.

One of the key parameters is the inclination angle (ϕ) of the heated surfaces. According to the published results, it is identified that the effects of the inclination angle on pool boiling are closely related with the geometries [4]. Many researchers had in the past generations investigated the effects of the orientation of a heated surface for the various combinations of geometries and liquids as listed in Table 1.

Summarizing the previous results it can be stated that heat transfer coefficients are dependent on the tube geometry and the heat flux of the lower tube. As already investigated by Kang [4], most published studies were for the tandem tubes in a vertical column arrangement. Only the effect of the elevation angle was investigated [4]. Therefore, the present study is aimed at the identification of the effects of ϕ and q''_L on pool boiling of the upper tube in a tube bundle. To the present author's knowledge, no results of this effect have as yet been published.

Table 1. Summary of Previous Investigations [4]

Author	Geometry	Liquid	Parameters
El-Genk & Bostanci (2003)	Flat plate	HFE-7100	ϕ=0°-180°
Stralen & Sluyter (1969)	Wire	Water	ϕ=0°,90°
Nishikawa et al. (1984)	Flat plate	Water	ϕ=0°-175°
Jung et al. (1987)	Flat plate	R-11	ϕ=0°-180° Enhanced surface
Fujita et al. (1988)	Parallel plates	Water	ϕ=0°-175° Gap size Flow confinement
Sateesh et al. (2009)	Single tube	Water Ethanol Acetone	ϕ=0°-90° Diameter Surface roughness
Narayan et al. (2008)	Single tube	Nano fluid	ϕ=0°-90° Particle concentration
Kang (2010)	Single tube Annulus	Water	ϕ=0°-90° Flow confinement
Kang (2014)	Tube inside	Water	ϕ=0°-90°

2. Experiments

For the tests, the assembled test section (Fig. 1) 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. 2. 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 (L). The tube was finished through a buffing process to have a smooth surface (roughness: R_a =0.15μm).

The inclination angle was changed from 0° to 90° by rotating the assembled tube assembly. The heat flux of the lower tube was (1) set fixed values of 0, 30, 60, and 90 kW/m^2 or (2) varied equal to the heat flux of the upper tube. The water tank was filled with the filtered tap water until the first water level reached 1.1 m; the water was then heated using four pre-heaters at constant power. When the water temperature was reached the saturation value (100 °C since all tests were done at atmospheric pressure), the water was then boiled for 30 minutes to remove the dissolved air. The temperatures of the tube surfaces (T_W) were measured when they were at steady state while controlling the heat flux on the tube surface with the input power.

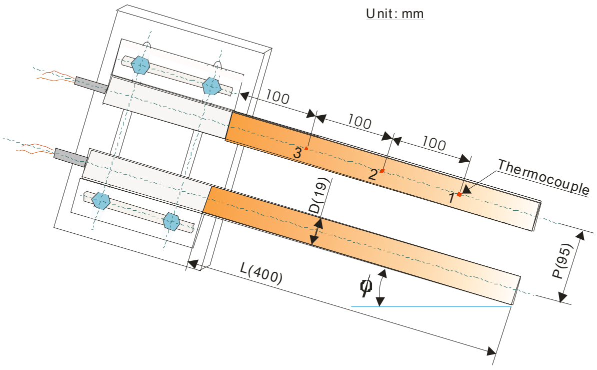

Fig. 1. Assembled test section.

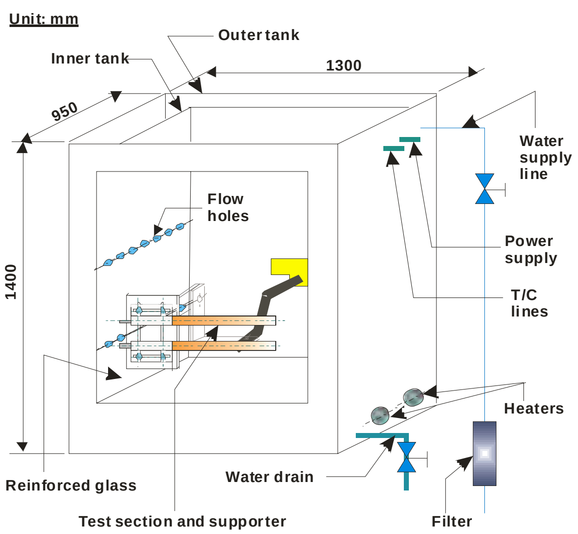

Fig. 2. Schematic of experimental apparatus.

The tube outside was instrumented with six T-type sheathed thermocouples (diameter is 1.5 mm). The thermocouple tip (about 10 mm) was brazed on the sides of the tube wall. The water temperatures were measured with six sheathed T-type thermocouples attached to a stainless steel tube that placed vertically in a corner of the inside tank. To measure and/or control the supplied voltage and current, two power supply systems were used.

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

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

where V and I are the supplied voltage and current, and D and L are the outside diameter and the length of the heated tube, respectively. T_W and T_{sat} represent the measured temperatures of the tube surface and the saturated water, respectively. Every temperature used in Eq. (1) is the arithmetic average value of the temperatures measured by the thermocouples.

The uncertainties of the experimental data were calculated from the law of error propagation [5]. 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 of 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%.

3. Results

Figure 3 shows plots of q''_T versus ΔT_{sat} data obtained from the experiments. The heat flux of the upper tube was varied for the different inclination angles when q''_L =0kW/m^2. The wall superheat increases as the inclination angle changes from the horizontal (ϕ =0°) to the vertical (ϕ =90°). The change of ϕ from 0° to 90° results in a 50% increase (from 6.2 to 9.3°C) of ΔT_{sat} when q''_T =30kW/m². The deterioration in heat transfer is clearly observed at low or moderate heat fluxes. When the inclination angle increases the duration time of the bubbles on the tube surface is increased. During the time the bubbles are moving along the tube and coalescing with the other bubbles to generate big size bubble slugs. This bubble slugs prevent the access of the environment liquid to the heated surface. Therefore, the heat transfer is deteriorated due to the increase of the inclination angle.

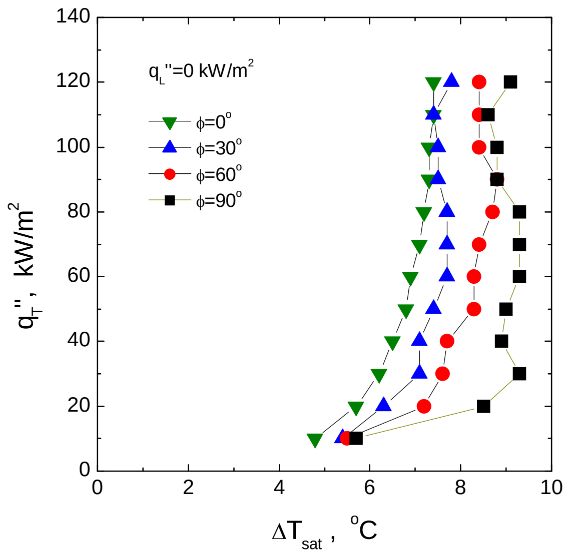

Fig. 3. Plots of q''_T versus ΔT_{sat} at q''_L =0kW/m^2.

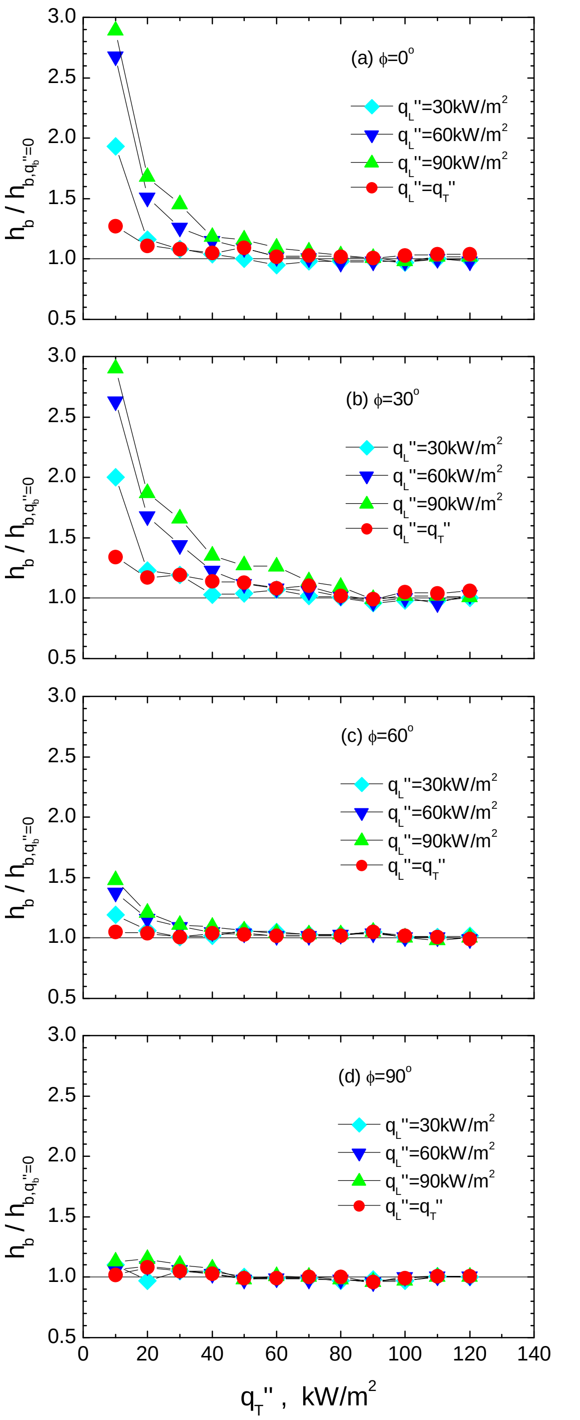

Fig. 4. Variations of bundle effect with ϕ and q''_L .

To identify the bundle effect the ratios of $h_b / h_{b,q''_L=0}$ were obtained for the different q''_L as the inclination angle changes from 0° to 90°. Results for the four inclination angle are shown in Fig. 4. The heat transfer is enhanced as q''_L is increased. However, heat transfer is deteriorated as the inclination angle is increased.

The bundle effect is clearly observed when $q''_L > q''_T$ and q''_T is less than 60 kW/m^2. 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 heat transfer gets deteriorated. 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 $\phi \le 30°$.

The increase of ϕ results in heat transfer decrease on the upper tube surface. The decrease in the bundle effect is clearly observed at $\phi \ge 60°$. The major cause of the heat transfer deterioration is due to the decrease of the affected area by the upcoming convective flow. The bundle effect is expected as the convective flow of bubbles and liquid, rising from the lower tube, enhances the heat transfer on the upper tube [2]. As the inclination angle increases part of the upper tube is relatively free from the upward flow. This results in the decrease of the bundle effect. This tendency becomes maximized as the bundle approaches to the vertical position. When ϕ =90° the convective flow has almost no effect on the heat transfer on the test tube and the value of h_r is nearby 1 regardless of the heat fluxes.

4. Conclusions

The effects of the inclination angle of the tube bundle and the heat flux of the lower tube on pool boiling heat transfer of the upper tube were investigated using a heated tube of 19 mm diameter and the water at atmospheric pressure. The increase in the heat flux of the lower tube and the decrease of the inclination angle increases the bundle effect. The increase in the bundle effect is clearly observed at $\phi \le 30°$ and q''_T <60 kW/m^2 when $q''_L > q''_T$. The major reason of the heat transfer enhancement on the upper tube is due to the convective flow and liquid agitation caused by the lower tube. The intensity of the effects is magnified when the tube bundle is in horizontal position.

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