Effects of Angle of Rotation on Pool Boiling Heat Transfer of V-shape Tube Bundle

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

One of the most effective ways to improve current pressurized water reactors is to adopt passive decay heat removal systems for the purpose of long-time core cooling without any external power supply and operator action. In the systems, water and/or steam circulate naturally to prevent core melting [1,2]. The most important facility for the systems is a passive heat exchanger that transfers core decay heat to the cold water in a water storage tank under atmospheric pressure. Since the space for the installation of the heat exchanger is usually limited, developing more efficient heat exchangers is important.

In general, pool boiling is generated on the surface of the heat exchanging tube. The major design parameter of the heat exchanger is a tube arrangement. The upper tube is affected by the lower tube and the enhancement of the heat transfer on the upper tube is estimated by the bundle effect [3]. Since heat transfer is related to the conditions of a tube surface, bundle geometries, and a liquid type, lots of studies have been carried out for the combinations of those parameters [4,5].

Since the source of the convective flow in pool boiling is the lower heated tube, the heat transfer change due to the heat flux of the lower tube (q''_L) is of interest. Ustinov et al. [6] investigated effects of the heat flux of the lower tube on pool boiling of the upper tube. They identified that the increase in the heat flux of the lower tube decreased the superheat (ΔT_{sat}) of the upper tube.

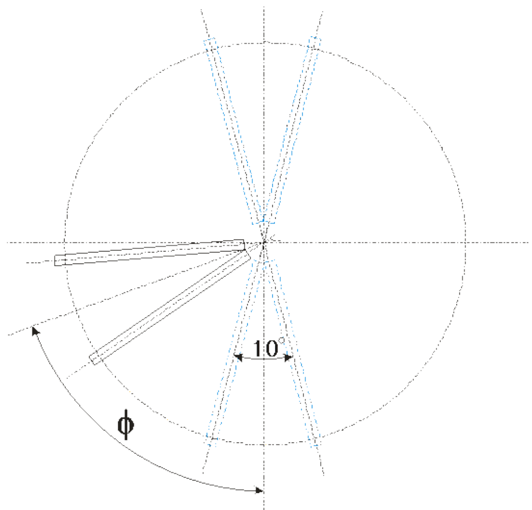

Fig. 1. Angle of rotation of V-shape tube bundle.

The passive condensers adopted in SWR1000 and APR+ has almost V-shape tube bundles [1,2]. Those tubes are slightly inclined from the horizontal to prevent the occurrence of the water hammer. Recently, Kang[7] studied the effects of the included angle and the heat flux of the lower tube on heat transfer enhancement of the upper tube, arranged one above the other in the same vertical plane. When the angle of rotation (ϕ, see Fig. 1) is changed the heat transfer coefficient (h_b) of the upper tube can be varied. Therefore, the present study is focused on the identification of the angle of rotation of V-shape tube bundles on pool boiling heat transfer. Up to the author's knowledge, no previous results concerning to this effect have been published yet. The results of this study could provide a clue to the thermal design of passive type heat exchangers with V-shape tube bundles.

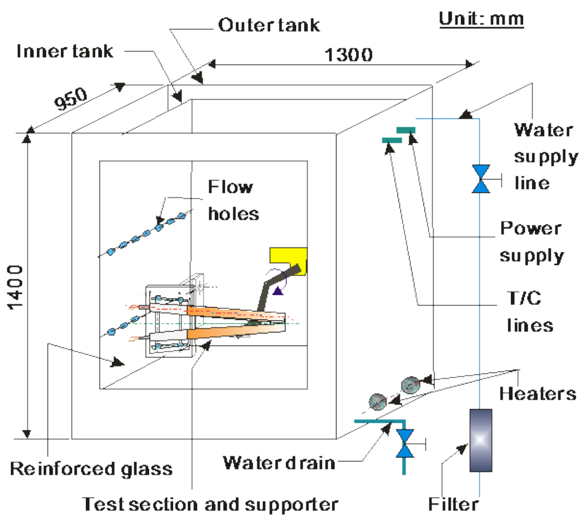

Fig. 2. Schematic of experimental apparatus.

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. 2. The heat exchanging tubes were resistance heaters made of a very smooth stainless steel tube of 19 mm diameter (D). The included angle for the test was set as 10°. The angle of rotation was changed from 0° to 180° in steps of 30° by rotating the tube assembly.

The tube outside was instrumented with six T-type sheathed thermocouples. The thermocouples were brazed on the sides of the tube. 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 were done at atmospheric pressure). To measure and/or control the supplied voltage and current, power supply systems were used.

After the water tank was filled with water until the initial 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, the water was then boiled for 30 minutes to remove the dissolved air. The temperatures of the tube surfaces were measured when they were at steady state while controlling the heat flux on the upper tube surface with input power.

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 [8]. The uncertainty of the measured temperature had 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 2 shows plots of q''_T versus ΔT_{sat} data obtained from the experiments. The q''_L was the same as q''_T. As shown in the figure the heat transfer on the upper tube is varied much as the angle of rotation changes from 0° to 180°. The superheating decreases as ϕ increases from 0° to 90°. However, ΔT_{sat} is increasing as ϕ increases from 90° to 180°. When q''_T =60kW/m^2, ΔT_{sat} decreases 25.3% (from 8.1 to 6.2°C) as ϕ increases from 0° to 90°. For the same heat flux, ΔT_{sat} increases 79% (from 6.2 to 11.1°C) as ϕ increases from 90° to 180°. Throughout the heat fluxes tested the enhancement in heat transfer is clearly observed at ϕ =90°. The maximum wall superheating is observed at ϕ =150° through the heat fluxes except $q''_T \leq 30$ kW/m^2, where the maximum is observed at ϕ =180°.

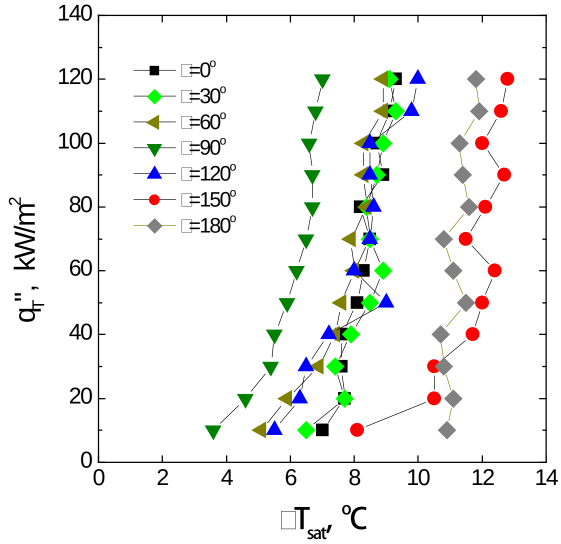

Fig. 3. Plots of q''_T versus ΔT_{sat}.

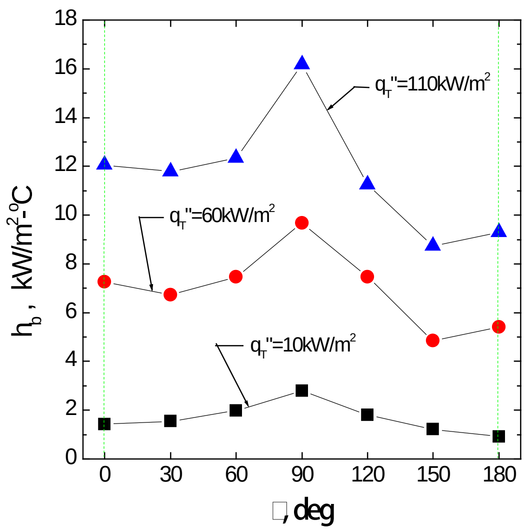

Fig. 4. Variations in heat transfer coefficient as rotation of angle changes.

The changes in heat transfer coefficients are plotted in Fig. 4 as the angle of rotation is varying from 0° to 180°. The maximum value is observed at ϕ =90°. Throughout the heat fluxes the ratio of $h_{b,\max} / h_{b,\min}$ is larger than 1.8. When q''_T =60kW/m^2, the ratio is almost 2. The largest ratio is observed when q''_T is in lower fluxes where the effect of the convective flow is dominant. The region of the upper tube influenced by the lower tube is varying as the angle of rotation changes. The region has the maximum at ϕ =90° where the maximum heat transfer coefficient is observed.

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 [9]. The intensity of the convective flow is increased as q''_L increases [7]. The heat transfer on the upper tube is associated with the bulk movement of bubble and liquid coming from the lower side [10]. The possible mechanisms affecting on heat transfer of the upper tube surface can be counted as the convective flow, liquid agitation, and bubble coalescence.

The convective flow generated by the bulk movement enhances heat transfer and is important for the heat transfer analysis, especially, at low heat fluxes. 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 convective flow gets decreased.

There seem to be two competing effects on the nucleate boiling heat transfer. One is the effect of liquid agitation by bubbles generated on the surface which enhances heat transfer and the other is the effect of bubble coalescence and the formation of large vapor slugs in the high heat flux region in particular which reduces heat transfer from the tube surface [11]. The intensity of the liquid agitation depends on a number of bubbles and the active movement of the bubbles. The enhancement in heat transfer shown in Fig. 4 at higher heat fluxes is closely dependent on the liquid agitation. The slight increase in h_b is observed at ϕ =0° and 180° when q''_T ≥60kW/m^2. At these angles, the upper tube is relatively free from the coalescence of bubbles coming from the lower tube. Therefore, the increase in heat flux is contributing to increasing the intensity of liquid agitation which enhancing heat transfer.

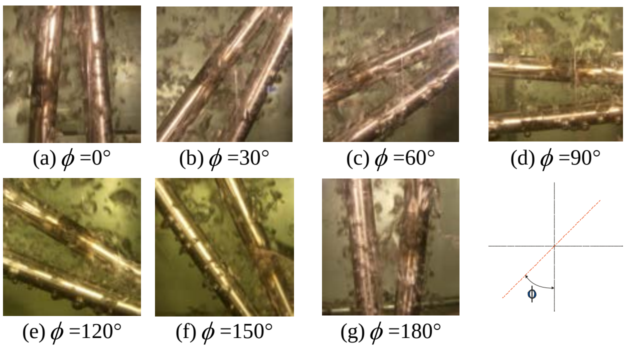

Fig. 5. Photos of pool boiling at q''_T =60kW/m^2.

Figure 5 shows some photos of pool boiling for V-shape tube bundle as the angle of rotation varies. Those photos were taken at around the mid region of the bundle. Relatively larger size bubbles are observed when ϕ is 90°. Because of the buoyancy, the bubbles move upward and the upper tube is affected by the flow of the bubble and the liquid.

4. Conclusions

An experimental study was performed to investigate the effects of the angle of rotation on pool boiling heat transfer of a V-shape tube bundle. For the test, two smooth stainless steel tubes of 19 mm outside diameter and the water at atmospheric pressure were used. The angle was varied from 0° to 180° in steps of 30°and the heat flux of the lower tube was set as equal to the upper tube. The enhancement of the heat transfer is clearly observed when the angle becomes to 90° where the upper tube has the maximum region of influence by the lower tube. The convective flow and liquid agitation enhance heat transfer while the coalescence of the bubbles deteriorates heat transfer.

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