Effects of Dihedral Angle on Pool Boiling Heat Transfer from Two Tubes in Vertical Alignment

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1. Introduction

Pool boiling is closely related with the design of passive type heat exchangers, which have been investigated in nuclear power plants to achieve safety functions in case of no power supply [1,2]. Since the space for the installation of a heat exchanger is usually limited, developing more efficient heat exchangers is important.

One of the major issues in pool boiling heat transfer 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 (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 [3]. Since heat transfer is related with 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].

The most effective parameter must be the tube pitch. Many researchers have been investigated its effect on heat transfer enhancement for the tube bundles [6-8] and the tandem tubes [9,10]. The heat transfer on the upper tube of the tubes is enhanced compared with the single tube [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]. It was explained that the major influential factor is the convective effects due to the fluid velocity and the rising bubbles [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. [12] investigated effects of the heat flux of lower tube on pool boiling of the upper tube for the fixed tube pitch. They used microstructure-R134a or FC-3184 combinations and identified that the increase in the heat flux of the lower tube decreased the superheat (ΔT_{sat}) of the upper tube.

The passive condensers adopted in SWR1000 and APR+ has U-type tubes [1,2]. Those tubes are slightly inclined from the horizontal to prevent the occurrence of the water hammer. Since the pitch between the upper and lower tubes is varying along the tube length, the results for the fixed pitch are not applicable to the analysis of these condensers. Although there are lots of studies introducing results for the effects of inclination angle on pool boiling heat transfer [13], no results are treating the angle between two tubes. Therefore, the present study is aimed to study the effects of the dihedral angle (α) 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.

Table 1. Test Matrix

α , deg	P/D	q''_L , kW/m²	q''_T , kW/m²
2	0.39	0,30,60,90, q''_T	10-120
6	1.16	0,30,60,90, q''_T	10-120
10	1.93	0,30,60,90, q''_T	10-120
14	2.69	0,30,60,90, q''_T	10-120
18	3.46	0,30,60,90, q''_T	10-120

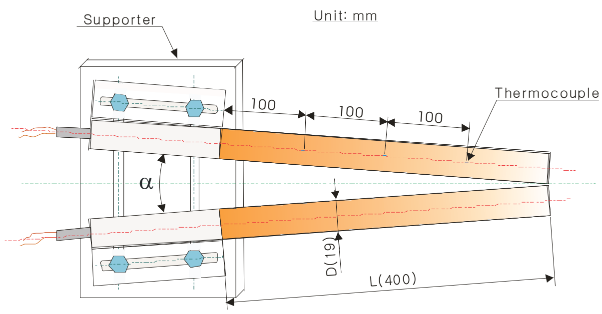

Fig. 1. Schematic diagram of test section.

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. The heat exchanging tube is a resistance heater made of a very smooth stainless steel tube of 19 mm diameter (D). The dihedral angle was regulated by adjusting the tubes, which were positioned one above the other and were assembled using bolts and nuts to the supporter.

The dihedral angle (shown in Fig. 1) between the tubes was varied from 2° to 18°. The inclinations of the upper and the lower tubes are same and equal to $\alpha/2$.

The increase in the dihedral angle changes the average pitch (P) between the tubes. The average pitches were calculated as $P = 420\sin(\alpha/2)$ since the tubes had unheated tip length of 10mm. Through the dihedral angles tested the average tube pitch varies from 7.33 to 65.67mm. The test matrix for the investigation is shown in Table 1. q''_T is the heat flux of the upper tube surface.

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 uncertainties of the experimental data were calculated from the law of error propagation [14]. 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 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%.

3. Results

Figure 2 shows plots of q''_T versus ΔT_{sat} data obtained from the experiments. The q''_L was changed for α =6°. 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 =0kW/m^2). The change of q''_L from 90 to 0kW/m^2 results in 51.2% (from 4.1 to 6.2°C) increase of ΔT_{sat} when q''_T =30kW/m^2. 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. When q''_T >80kW/m^2 the curve for $q''_L \neq 0$kW/m^2 converges to the curve for the single tube.

The result for $q''_L = q''_T$ is very unique comparing to the other results. The curve for $q''_L = q''_T$ shows a kind of transition from enhanced to deteriorated heat transfer as q''_T decreases. When q''_T is lower than 30kW/m^2, the tube wall superheat is higher than the curve for q''_L =30kW/m². As the heat flux increases, the curve for q''_T versus ΔT_{sat} shift left side and the enhancement of heat transfer is observed. When q''_T >80 kW/m² the curve converges to the curve for q''_L =90kW/m².

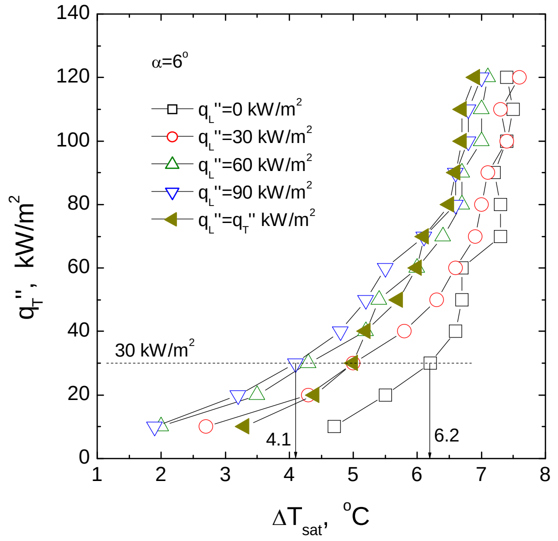

Fig. 2. Plots of q''_T versus ΔT_{sat} .

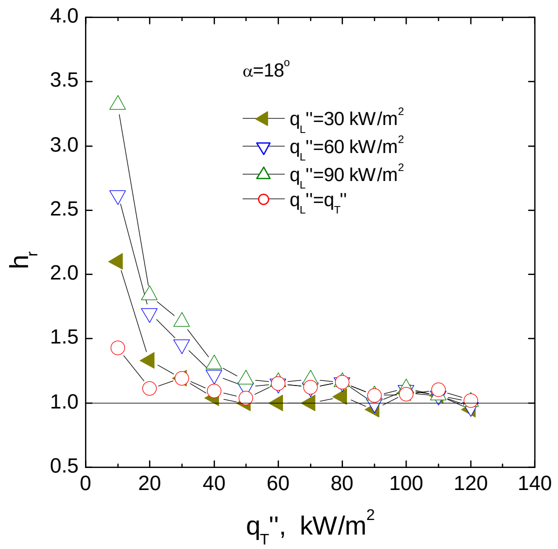

Fig. 3. Variations in bundle effect for α =18°.

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 [10]. The intensity of the convective flow is increased as q''_L increases. The heat transfer on the upper tube is associated with (1) the bulk movement of bubble and liquid coming from the lower side and (2) micro-convective component relates to the heat transfer associated with the bubble nucleation and growth on the tube surface [9]. The possible mechanisms affecting on heat transfer on the upper tube surface can be counted as convective flow, liquid agitation, and the nucleation site density. The increase in the heat flux also results in the increase in the nucleation sites which increase heat transfer. The convective flow generated by the bulk movement enhances heat transfer and is important for the heat transfer analysis, especially, at low heat fluxes. The liquid agitation also enhances heat transfer. The intensity of the liquid agitation depends on the amount of bubbles and the active movement of the bubbles. 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 the enhancement in heat transfer gets decreased.

Figure 3 shows variations in the bundle effect against the heat flux on the upper tube for the dihedral angle of 18°. 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. Significant bundle effect has been found at q''_T is less than 60kW/m^2. However, the bundle effect converges to unity at higher heat fluxes regardless of the heat flux on the lower tube. Throughout the heat fluxes tested, the increases in q''_L increases the bundle effect.

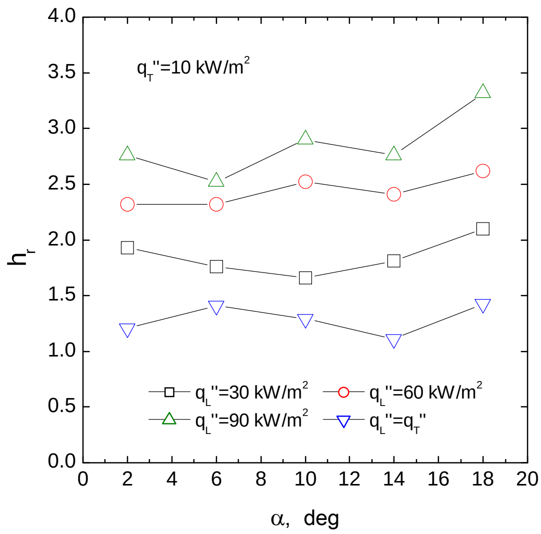

Fig. 4. Plots of h_r versus α at q''_T =10kW/m^2.

To identify the bundle effect the ratios of $h_b / h_{b,q''_L=0}$ were obtained for the different q''_L as the dihedral angle changes from 2° to 18°. Results for q''_T =10kW/m^2 are shown in Fig. 4. The increase of α varies heat transfer on the upper tube surface. The tendency is dependent on the heat fluxes. However, the increase in α eventually increases h_r. The enhancement is magnified as the heat flux of the lower tube is increased. When α changes from 2° to 18° the value of h_r increases about 20.3% for q''_L =10kW/m^2. This effect is strongly observed at the heat fluxes where the convective effect is dominant. The convective term becomes effective as q''_T is low and q''_L is high and $q''_L > q''_T$. The heat transfer enhancement becomes decreased as the heat flux on the upper tube is increased.

The bubbles departed from the lower tube need some distance to generate enough turbulent effect, which agitates relevant liquid to increase heat transfer coefficient. Therefore, the increase in the dihedral angle results in heat transfer enhancement for the present experimental ranges. Another related cause is the static pressure of the liquid. The size of the departed bubbles gets increased while moving upward due to the decrease of the static pressure. The big size bubbles generate active liquid agitation which enhances heat transfer.

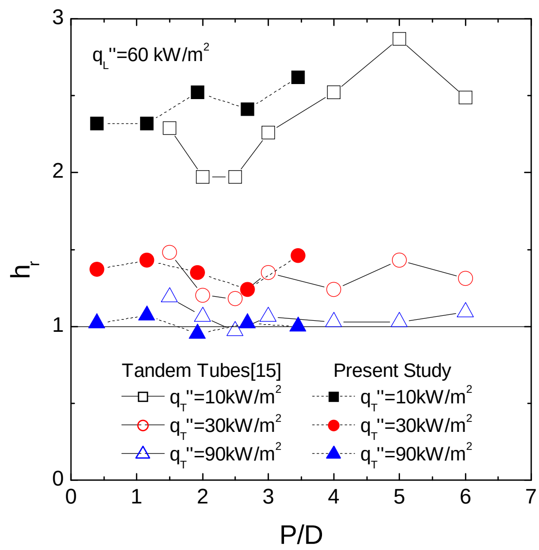

Fig. 5. Comparison of present data with published results.

The variations of the bundle effect for the different P/D and q''_T are shown in Fig. 5 for q''_L =60kW/m^2. In the figure results of the present study are compared with the published results for tandem tubes [15]. The tendencies of the two cases are very similar. However, the values of h_r for the present study are slightly higher than the tandem tubes. This is because of the sliding bubbles on the tube surface. If a tube is inclined bubbles are moving along the tube length and this generates additional liquid agitation. Its effect is clearly observed where the convective term is dominant.

4. Conclusions

The combined effects of the dihedral angle and the heat flux of the lower tube on heat transfer enhancement of the upper tube were investigated. The increase in α eventually increases h_r. When α changes from 2° to 18° the value of h_r increases about 20.3% for q''_L =10kW/m^2. The enhancement is clearly observed at the heat fluxes where the convective effect is dominant. The results of the present study were compared with the results of the tandem tubes and two cases show similar tendencies. However, the values of h_r for the present study are slightly higher than the tandem tubes.

REFERENCES

[1] A. Schaffrath, E. F. Hicken, H. Jaegers, H.M. Prasser,, Operation Conditions of the Emergency Condenser of the SWR 1000, Nucelar Engineering and Design, Vol. 188, p. 303, 1999.
[2] B. U. Bae, B. J. Yun, S. Kim, K. H. Kang, Design of Condensation Heat Exchanger for the PAFS (Passive Auxiliary Feedwater System) of APR+ (Advanced Power Reactor Plus), Annala of Nuclear Energy, Vol. 46, p. 134, 2012.
[3] S. B. Memory, S. V. Chilman, P. J. Marto, Nucleate Pool Boiling of a TURBO-B Bundle in R-113, ASME J. Heat Transfer, Vol. 116, p. 670, 1994.
[4] L. Aprin, P. Mercier, L. Tadrist, Local Heat Transfer Analysis for Boiling of Hydrocarbons in Complex Geometries: A New Approach for Heat Transfer Prediction in Staggered Tube Bundle, Int. J. Heat Mass Transfer, Vol. 54, p. 4203, 2011.
[5] A. Swain, M. K. Das, A Review on Saturated Boiling of Liquids on Tube Bundles, Heat Mass Transfer, DOI 10.1007/s00231-013-1257-1, published online: 26 Nov. 2013.
[6] Z.-H. Liu, Y.-H. Qiu, Boiling Heat Transfer Enhancement of Water on Tubes in Compact In-Line Bundles, Heat Mass Transfer, Vol. 42, p. 248, 2006.
[7] G. Ribatski, J. Jabardo, E. Silva, Modeling and Experimental Study of Nucleate Boiling on a Vertical Array of Horizontal Plain Tubes, Applied Thermal and Fluid Science, Vol. 32, p. 1530, 2008.
[8] A. Gupta, Enhancement of Boiling Heat Transfer in a 5×3 Tube Bundle, Int. J. Heat Mass Transfer, Vol. 48, p. 3763, 2002.
[9] A. Gupta, J. S. Saini, H. K. Varma, Boiling Heat Transfer in Small Horizontal Tube Bundles at Low Cross-Flow Velocities, Int. J. Heat Mass Transfer, Vol. 38, p. 599, 1995.
[10] E. Hahne, Chen Qui-Rong, R. Windisch, Pool Boiling Heat Transfer on Finned Tubes –an Experimental and Theoretical Study, Int. J. Heat Mass Transfer, Vol. 34, p. 2071, 1991.
[11] Z.-H. Liu, Y.-H. Qiu, Enhanced Boiling Heat Transfer in Restricted Spaces of a Compact Tube Bundle with Enhanced Tubes, Applied Thermal Engineering, Vol. 22, p. 1931, 2002.
[12] A. Ustinov, V. Ustinov, J. Mitrovic, Pool Boiling Heat Transfer of Tandem Tubes Provided with the Novel Microstructure, Int. J. Heat Fluid Flow, Vol. 32, p. 777, 2011.
[13] M. G. Kang, Pool Boiling Heat Transfer on the Inside Surface of an Inclined Tube, JP Journal of Heat and mass Transfer, Vol. 10, p. 47, 2014.
[14] H.W. Coleman, W.G. Steele, Experimentation and Uncertainty Analysis for Engineers, 2nd Ed., John Wiley & Sons, 1999.
[15] M. G. Kang, Pool Boiling Heat Transfer from Two Horizontal Tubes in Vertical Alignment, Transactions of the Korean Nuclear Society Spring Meeting, May 29-30, 2014, Jeju, Korea.