Effects of Tube Pitches on Pool Boiling Heat Transfer

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1. Introduction

The mechanism of pool boiling heat transfer has been studied for the past several decades since it is important to maintain the inherent heat removal capability without the power supply. One of the major issues for the design of a passive type heat exchanger is the identification of the effects of relevant tubes on heat transfer. The enhancement in heat transfer by the lower tube is defined as a bundle effect [1]. Most studies were focused on the tube bundles to apply to a flooded evaporator [2-4].

Many researchers have investigated the effect of tube spacing on heat transfer for the tube bundles [4-6] and the tandem tubes [7,8]. The heat transfer of the upper tube 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 geometry of a tube array was also studied to identify its effect on heat transfer enhancement 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 then, 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 useful results were observed 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.

Along with the tube spacing, its location is also of interest. If the upper tube is not in vertical alignment with the lower tube, the effect of the flow coming from the lower tube on heat transfer of the upper tube will be changed. To identify its effect Kang [13] studied about an elevation angle (γ) of the tandem tubes. If the elevation angle changes, both pitches of horizontal (P_h) and vertical (P_v) directions are varied. The increases of the elevation angle and the heat flux of the lower tube enhance heat transfer on the upper tube surface.

In the present study, the vertical pitch is fixed, and the horizontal one gets changed. This kind of study is valuable because the exact identification of the effect of the lower tube on heat transfer of the upper tube is important for the design of a heat exchanger.

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. P_v (shown in Fig. 2) was fixed as 38 mm . P_h was varied from 0.0 to 76.0 mm. Therefore, the pitches divided by the diameter are P_v / D =2.0 and P_h / D =0.0~4.0 as listed in Table 1. 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).

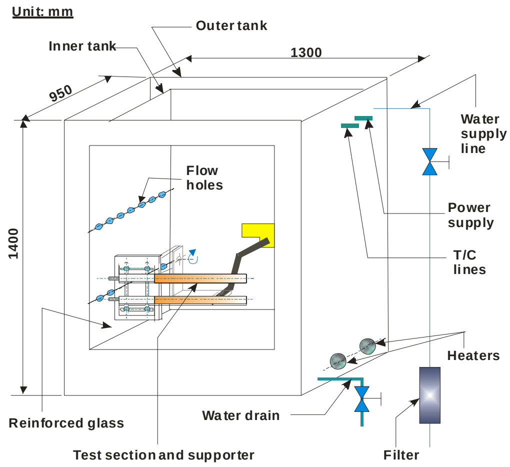

Fig. 1. Schematic of experimental apparatus.

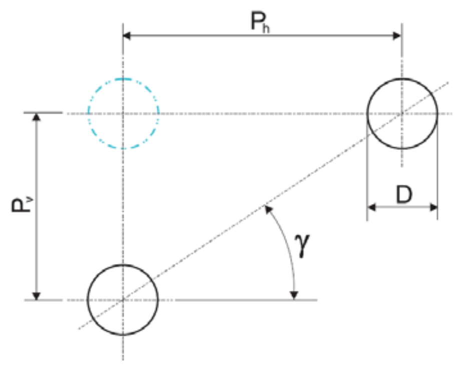

Fig. 2. Tube pitches of tandem tubes.

Table 1. Test Matrix

P_h	P_h / D	q''_L , kW/m²	q''_T , kW/m²

0.0	0.0	0,30,60,90, q_T''	10-120
9.5	0.5	0,30,60,90, q_T''	10-120
19.0	1.0	0,30,60,90, q_T''	10-120
28.5	1.5	0,30,60,90, q_T''	10-120
38.0	2.0	0,30,60,90, q_T''	10-120
57.0	3.0	0,30,60,90, q_T''	10-120
76.0	4.0	0,30,60,90, q_T''	10-120

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 (diameter is 1.5 mm). The thermocouple tip (about 10 mm) was brazed on the sides of the tube wall. The temperature decrease through the brazing metal was calibrated by the one dimensional conduction equation. Since the thermal conductivity of the brass is nearby 130W/m-ºC at 110ºC [14], the maximum temperature decrease through the metal is 0.08ºC at 110kW/m^2. The measured temperatures were calibrated considering the above error. 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 uncertainties of the experimental data were calculated from the law of error propagation [15]. 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. 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 lower tube was changed for P_h / D =0.0. 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 90 to 0 kW/m^2 results in 31.9% (from 4.7 to 6.2°C) increase of ΔT_{sat} when q_T'' =30kW/m². The gradual increase of q_L'' results in the decrease of ΔT_{sat} for the given heat flux. Throughout the heat fluxes tested the enhancement in heat transfer is much clearly observed at q_T'' ≤60kW/m². No clear difference is observed at higher heat fluxes.

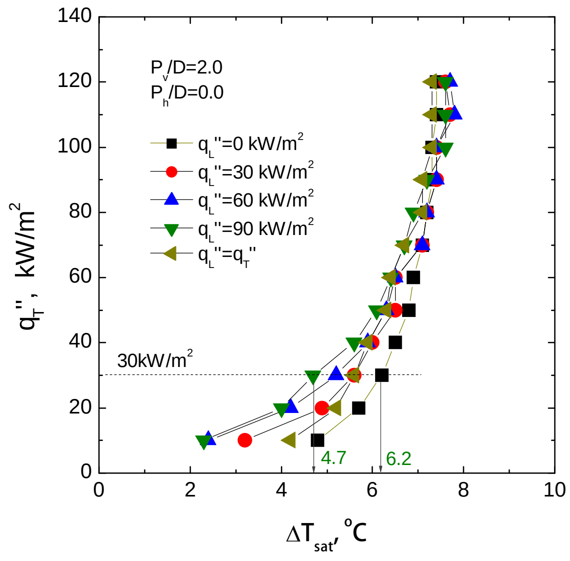

Fig. 3. Plots of q_T'' versus ΔT_{sat} for P_h / D =0.

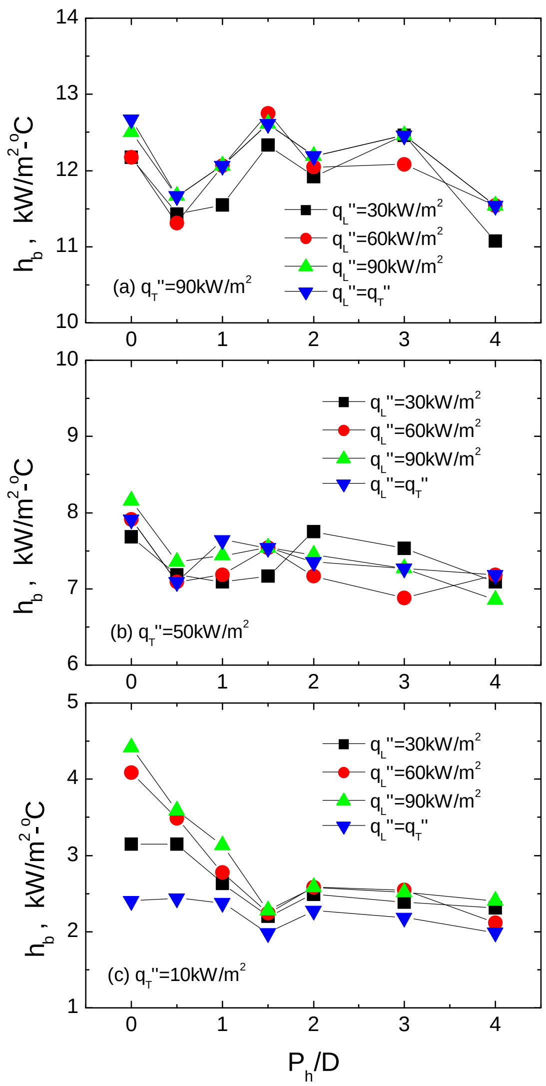

Fig. 4. Plots of h_b versus P_h / D.

To identify the effects of the upper tube location on heat transfer, h_b of the upper tube is plotted against P_h/D for the different heat fluxes of the lower tube. Results for the three q''_T are shown in Fig. 4. The heat transfer coefficient is eventually decreasing as P_h/D is increasing. The tendency is clearly observed at the low heat fluxes. However, the tendency is not unanimous and is dependent on q''_T. At q''_T =90 kW/m^2, the heat transfer coefficient is increasing as P_h/D increases at 0.5< P_h/D ≤1.5. Although the point is not the same, similar tendency is observed at q''_T =10 and 50kW/m^2.

The upward flow of liquid and bubbles disperses moving along the height and affects the heat transfer of the upper tube. The intensity of the flow is dependent on the heat flux of the lower tube and the location of the tubes. When the horizontal pitch increases effects of the upward flow on the upper tube get decreased. This is the major cause of the heat transfer decrease. As already explained by the researchers, convection-controlled regime prevails as the upper tube is at low heat fluxes [3]. Therefore, a clear decrease of h_b is observed when P_h/D increases at q''_T =10kW/m^2.

As the heat flux of the upper tube increases the major heat transfer mechanism is changing to the effects of bubbles. That is, liquid agitation generated by the bubbles, coalescence of bubbles, and a number of nucleation sites [13]. Since the upward flow is not the major cause of the heat transfer of the upper tube, no clear change of h_b is observed at q''_T =90kW/m^2 when regardless of P_h/D increase and the q''_L variation.

One of the possible explanations for the increase of h_b for some region of the P_h/D increase is due to the interference generated by the upward flow. The upward flow not only generates the convective flow but also interferes the bubble behavior on the upside tube. Therefore, the bubbles generating on the upper tube can be detached before the enough development in size. This decreases the portion of the latent heat on the upper tube and decreases heat transfer.

The mechanism of bubble coalescence is of meaningful consideration at higher heat fluxes. This is usually counted as the major cause of the deterioration in heat transfer [13]. The coalescence of the bubbles can be accelerated by the upward bubbles. Therefore, h_b decreases as P_h/D ≤0.5. As P_h/D increases the chance of the coalescence decreases. Through the P_h/D values the agitation of liquid generated by the upcoming bubbles is of a considerable cause of the heat transfer enhancement. The gradual increase of P_h/D decreases the intensity of liquid agitation and deteriorates heat transfer.

4. Conclusions

The effects of the horizontal pitch and the heat flux of the lower tube on the heat transfer coefficient were studied using the tandem tubes submerged in the water at atmospheric pressure. The increase of q''_L enhances heat transfer, especially at low q''_T, while the increase of P_h/D eventually deteriorates heat transfer. The major causes of the tendency are closely related to the convection flow and the interference generated by the upward flow of liquid and bubbles.

REFERENCES

[1] 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.

[2] 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.

[3] 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.

[4] 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.

[5] 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.

[6] A. Gupta, Enhancement of Boiling Heat Transfer in a 5×3 Tube Bundle, Int. J. Heat Mass Transfer, Vol. 48, p. 3763, 2002.

[7] 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.

[8] 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.

[9] P. J. Nelson, B. M. Burnside, Boiling the Immiscible Water/n-nonane System from a Tube Bundle, Int. J. Heat Mass Transfer, Vol. 28, p. 1257, 1985.

[10] S.-S. Hsieh, G.-Z. Huang, H.-H. Tsai, Nucleate Pool Boiling Characteristics from Coated Tube Bundles in Saturated R-134a, Int. J. Heat Mass Transfer, Vol. 46, p. 1223, 2003.

[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, Effects of Elevation Angle on Pool Boiling Heat Transfer of Tandem Tubes, Int. J. Heat Mass Transfer, Vol. 85, p. 918, 2015.

[14] J. P. Holman, Heat Transfer, 8th ed., McGraw-Hill, 1997.

[15] H.W. Coleman, W.G. Steele, Experimentation and Uncertainty Analysis for Engineers, 2nd Ed., John Wiley & Sons, 1999.