Effects of Tube Pitch on Pool Boiling Heat Transfer of Horizontal Tube Bundle

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1. Introduction

One of the major issues in the design of a passive type heat exchanger is to investigate the effect of a tube pitch (P) on pool boiling heat transfer. Recently, a passive type heat exchanger has been adopted in nuclear power plants to meet safety functions in case of no power supply [1,2]. The heat exchangers have many heat exchanging tubes. Since the heat transfer of a tube is closely related to the relevant tubes, the results for a single tube are not applicable to the tube bundles.

For a horizontal tube bundle in vertical alignment, the heat transfer on the upper tube is enhanced compared with the single tube [3]. It was explained that the major influencing factor is the convective effects due to the fluid velocity and the rising bubbles [4]. Ustinov et al. [5] investigated effects of the heat flux of the lower tube on pool boiling of the upper tube for the fixed tube pitch and identified that the increase in the heat flux of the lower tube decreased the superheating (ΔT_{sat}) of the upper tube. Recently, Kang [6] studied the effects of a tube pitch as well as the heat flux of a relevant tube on the heat transfer of a tube bundle installed vertically.

Summarizing the previous results it can be stated that heat transfer coefficients are highly dependent on the tube pitch and the heat flux of the relevant tube. Although the published results are mostly about the horizontal tubes, there is still an obscure area to be identified. Therefore, the focus of the present study is an identification of the effects of a tube pitch as well as the heat flux of a relevant tube on the heat transfer of a tube bundle installed horizontally.

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 (L). The tube was finished through a buffing process to have a smooth surface. The arithmetic mean of all deviations from the center line of the sampling path had the value of R_a =0.15μm. Electric power of 220 V AC was supplied through the bottom side of the tube.

The pitch was changed from 28.5 to 95 mm by adjusting the space between the tubes. The heat flux of the left- hand side tube (q''_L) was (1) set fixed values of 0, 30, 60, and 90 kW/m^2 or (2) varied equal to the heat flux of the right-hand side tube (q''_T). 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 boiled for 30 min to remove the dissolved air. The temperatures of the tube surfaces were measured when they were at steady state while controlling the heat fluxes of the tubes with the input power.

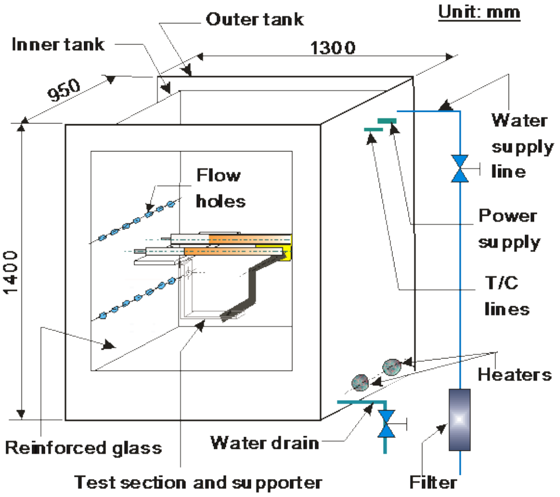

Fig. 1. Schematic of experimental apparatus.

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.

The uncertainties of the experimental data were calculated from the law of error propagation [7]. 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%. The uncertainty of the heat transfer coefficient was calculated through a statistical analysis of the results of $q''_T / \Delta T_{sat}$ and was determined to be ±6%.

3. Results

To identify the effects of a relevant tube the ratios of $h_b / h_{b,q_L''=0}$ were plotted against q_T'' for the different q_L''. When the value of q_L'' is increased the enhancement of heat transfer is observed as shown in Fig. 2. The increase in heat transfer is obvious when the value of the heat flux of the test section (q_T'') is at low heat fluxes less than 40 kW/m^2. The heat transfer coefficient is enhancing more than 40% at q_T'' =10kW/m^2 and q_L'' =90kW/m^2 comparing to the case of the relevant tube is not activated.

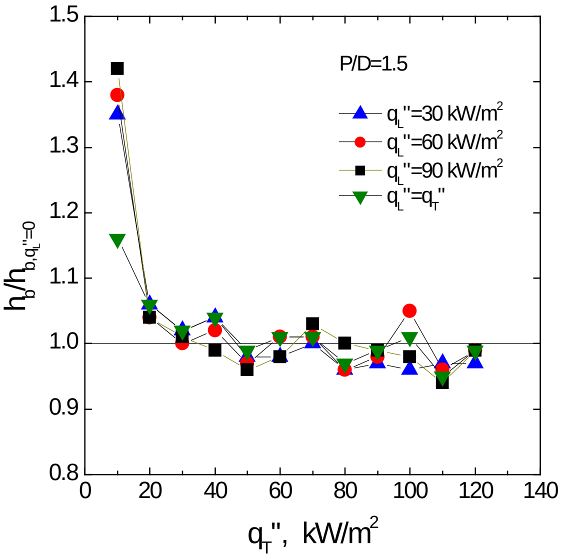

Fig. 2. Plots of $h_b / h_{b,q_L''=0}$ versus q_T'' for P/D=1.5.

Figure 3 shows the variations of the heat transfer coefficient for the different q_L'' and q_T''. To identify the pitch effect on heat transfer experimental data for both horizontal and vertical tubes are plotted as P/D varies from 1.5 to 5. When the tubes are in vertical direction [6], the enhancement of heat transfer is observed as the value of P/D is decreased as shown in Fig. 3. The enhancement is clearly observed when q_T'' =20kW/m^2 and q_L'' =90kW/m^2. However, the effect of the tube pitch is not obvious when the tubes are in a horizontal direction. The effect of the tube pitch on heat transfer is negligible as the value of P/D is increased more than 4 regardless of the tube direction.

The enhancement of the heat transfer is mainly due to the increase in the intensity of the liquid agitation generated by the moving bubbles. The bubbles generated at the lower regions move to the upside. When a bubble is detached from the surface and moved along the surface space is created. Then, the environment liquid rushes into space and, as a result, active liquid agitation is created around the surface. The effect of liquid agitation is dominant throughout the heat fluxes and is dependent on the active movement and the amount of the bubbles.

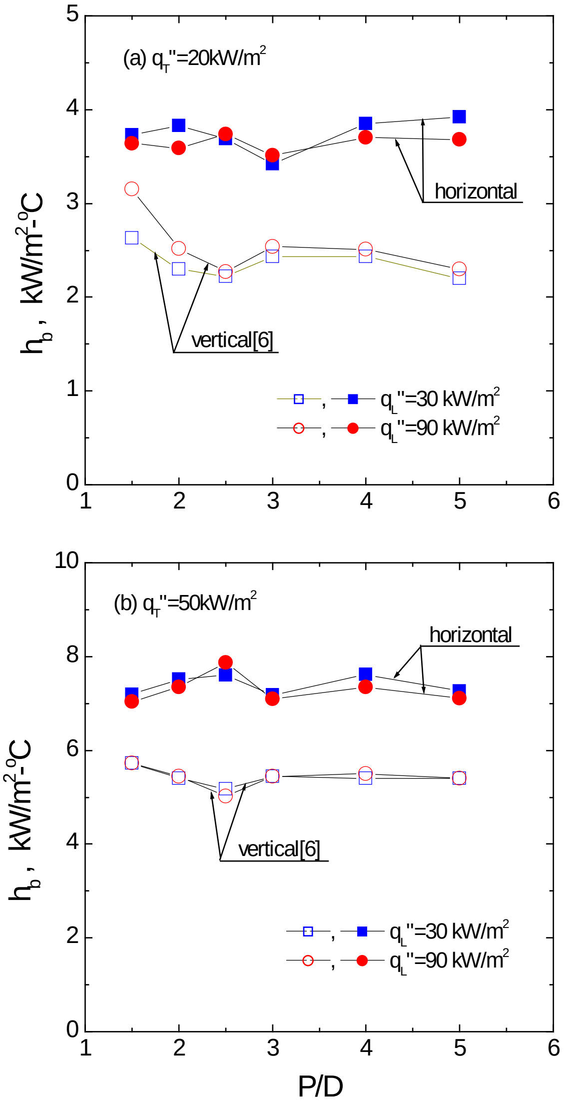

Fig. 3. Variations in heat transfer with P/D and q_L''.

The convective flow generated by the relevant tube also enhances heat transfer and is important for the heat transfer analysis at low heat fluxes. When the test section is at low heat flux a convection-controlled regime prevails [4]. However, as the heat flux of the tube increases and the value of P/D increases, the portion of the liquid convection gets decreased and, accordingly, the enhancement in heat transfer gets decreased. When the tube is in a vertical direction, the upside flow spread broadly as it flows upward through the tube and this changes the heat transfer of the relevant tube. If the tubes are in a horizontal direction, the affected region by the convective flow is small. Therefore, the variation of P/D cannot change the heat transfer much because the effect of convective flow on heat transfer of horizontal tubes is not significant.

The slight increase in heat transfer for the horizontal tubes can be explained by the circulating flow inside the water tank. Since the length of bubble movement is not long when the tubes are in horizontal direction, the effect of convective flow is relatively weak. For the case, the circulating flow does a significant role in heat transfer.

When the heat flux is increased many bubbles are generating due to the increase of the nucleation sites. The bubbles become coalescing with the nearby bubbles and generate big bunches of bubbles on the tube surface. This prevents the access of the liquid to the surface and deteriorates heat transfer. The bubble coalescence is competing with the mechanisms enhancing heat transfer and deteriorating heat transfer.

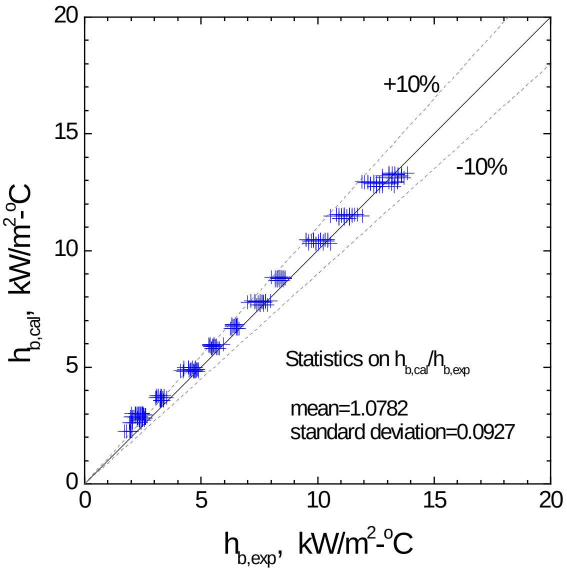

Fig. 4. Comparison of experimental data to calculated values.

To identify the validity of the present study, the experimental data were compared with the calculated results by the published correlation [8]. Most of the data points are within ±10 % of the calculated heat transfer coefficients as plotted in Fig. 4. The results of the statistical analyses on the ratios of the measured and the calculated heat transfer coefficients (i.e., $h_{b,cal} / h_{b,\exp}$) show that the mean and the standard deviation are 1.0782 and 0.0927, respectively.

4. Conclusions

An experimental study was performed to investigate the combined effects of a tube pitch and the heat flux of the nearby tube on pool boiling heat transfer of a horizontal tube bundle. For the test, two smooth stainless steel tubes of 19 mm outside diameter and the water at atmospheric pressure were used. The pitch was varied from 28.5 mm to 95 mm and the heat flux of the nearby tube was changed from 0 to 90kW/m^2. The enhancement of the heat transfer is clearly observed when the heat flux of the nearby tube becomes larger and the heat flux of the upper tube is less than 40kW/m^2. The effect of the tube pitch on heat transfer is negligible as the value of P / D is increased more than 4. The circulating flow, convective flow and liquid agitation enhance heat transfer while the coalescence of the bubbles deteriorates heat transfer.

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