Effect of Tube Pitch on Pool Boiling Heat Transfer of Vertical Tube Bundle

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1. Introduction

Pool boiling 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 [1,2]. One of the major issues in the design of a heat exchanger is the heat transfer in a tube bundle. 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.

One of the important parameters in the analysis of a tube bundle is the pitch (P) between tubes [3]. For a horizontal tube bundle in vertical alignment, the heat transfer on the upper tube is enhanced compared with the single tube [4]. It was explained that the major influencing factor is the convective effects due to the fluid velocity and the rising bubbles [5]. Ustinov et al. [6] 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 [3] studied the combined effects of a tube pitch and the heat flux of a lower tube on saturated pool boiling heat transfer of tandem tubes experimentally.

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. The published results are mostly about the horizontal tubes. However, there are many heat exchangers consisting of vertical tubes like AP600 [1]. 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 vertically.

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 pitch was changed from 28.5 to 95 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 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 fluxes of the tubes with the input power.

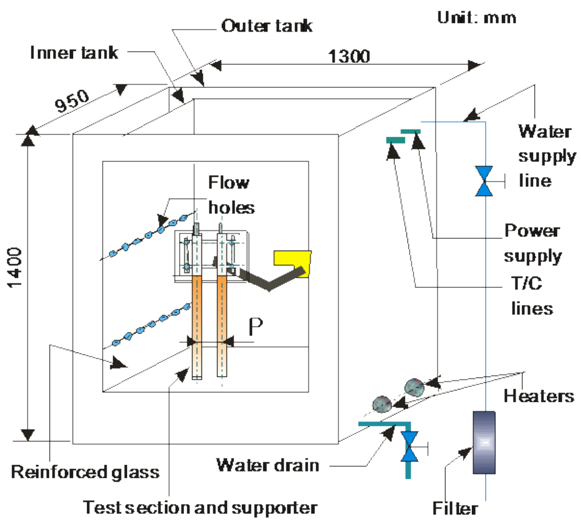

Fig. 1. Schematic of experimental apparatus.

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 pitch effect the ratios of $h_b / h_{b,q_L''=0}$ were obtained for the different q_L'' as P/D changes from 1.5 to 5. When the value of P/D is decreased the enhancement of heat transfer is observed as shown in Fig. 2. The increase in heat transfer is obvious when the value of q_L'' is large and the heat flux of the test section (q_T'') is at low heat fluxes less than 40 kW/m^2. However, the effect of the tube pitch on heat transfer is negligible as the value of P/D is increased more than 4. When P/D=5, the heat transfer coefficient of the bundle is slightly smaller than that of the single tube.

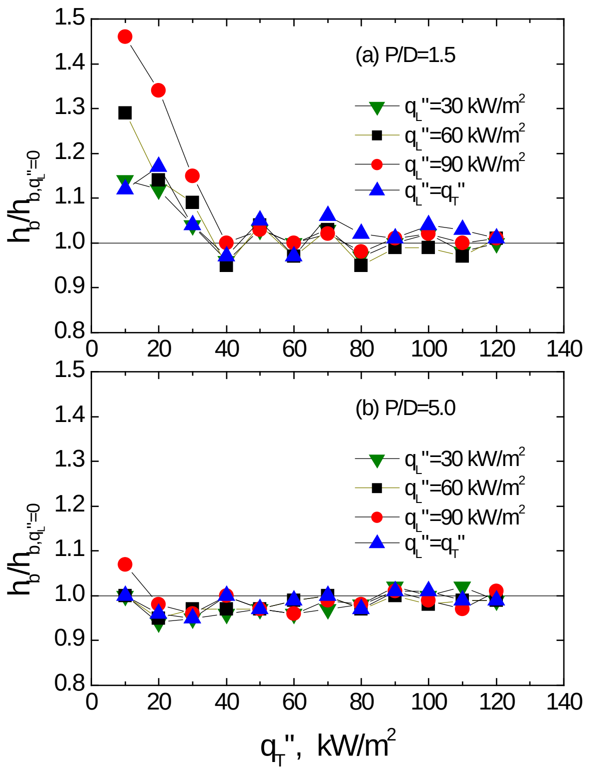

Fig. 2. Variations in heat transfer with P/D and q_L''.

The possible mechanisms enhancing the heat transfer from the tube surface can be counted as liquid agitation and convective flow. The enhancement of the heat transfer is mainly due to the increase of the intensity of the liquid agitation generated by the moving bubbles. Since the tube is in a vertical orientation, the bubbles generated at the lower regions move to the upside and generate active liquid agitation around the surface. The effect of the liquid agitation is dominant throughout the heat fluxes and is dependent on the active movement and the amount of the bubbles.

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 [3]. The combined effect of the liquid agitation and the convective flow increases heat transfer. 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. Since the mixed flow of bubble and liquid goes upward due to the buoyancy, the increase of the pitch decreases the effects of the convective flow on 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 generates 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.

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 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 convective flow and liquid agitation enhance heat transfer while the coalescence of the bubbles deteriorates heat transfer.

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