Effects of Overlap Length on Pool Boiling from Two Horizontal Tubes in Vertical Alignment

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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 [3].

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 of 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 P =27mm 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.

Since the enhancement in heat transfer of the upper tube is due to the lower side tube, the overlap length is of importance. If the length gets shorter it is expected that effects of the convective flow and bubbles generated by the lower tube become weaker. Summarizing the previous results it can be stated that heat transfer coefficients are highly dependent on the heat flux of the relevant tube. Therefore, the focus of the present study is an identification of the effects of an overlap length as well as the heat flux of a lower side tube on the heat transfer of an upper tube in a vertical alignment.

2. Experiments

For the tests, the assembled test section was located in a water tank which had a rectangular cross section (950×1300mm) and a height of 1400mm as shown in Fig. 1. The heat exchanging tube is a resistance heater made of a very smooth stainless steel tube of 19mm outside diameter (D) and 400mm heated length (L). The layout of the tubes is shown in Fig. 2. The tube was finished through a buffing process to have a smooth surface. The value of the surface roughness was measured by a stylus type profiler. The arithmetic mean of all deviations from the center line over the sampling path has the value of R_a =0.15μm. Electric power of 220V AC was supplied through the bottom side of the tube.

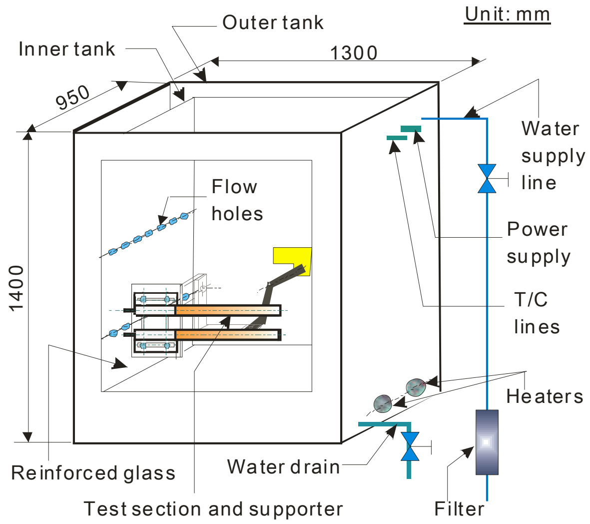


Fig. 1. Schematic of experimental apparatus.

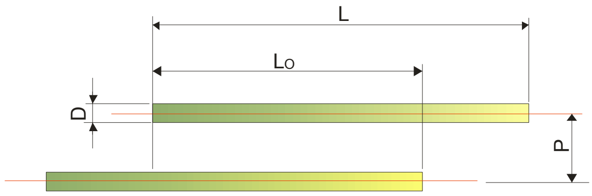


Fig. 2. Layout of tubes in vertical alignment.

The tube outside was instrumented with six T-type sheathed thermocouples (diameter is 1.5mm). The thermocouple tip (about 10mm) 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 ratio of the overlap length (L_O) to the heated length was changed from 1/2 to 1 in steps of 1/4. The heat flux of the lower side tube (q_L'') was (1) set fixed values of 0 and 60 kW/m^2 or (2) varied equally to the heat flux of the upper side tube (q''_T). The water tank was filled with the filtered tap water until the first water level reached 1.1m; 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 30min 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. The test matrix for the investigation is shown in Table 1.

Table 1. Test matrix

P, mm	L_o/L	q''_L, kW/m²	q''_T, kW/m²
47	1/2	0,60, q''_T	10-120
	3/4	0,60, q''_T	10-120
	1	0,60, q''_T	10-120
165	1/2	0,60, q''_T	10-120
	3/4	0,60, q''_T	10-120
	1	0,60, q''_T	10-120

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

Figure 3 shows plots of q''_T versus ΔT_{sat} data obtained from the experiments. The q''_L was changed for L_o/L =1/2 and 1. As shown in the figure, the heat transfer of the upper is enhanced compared with the single tube (i.e., q''_L =0kW/m^2) regardless of the overlap length. The enhancement is clearly observed at L_o/L =1. The gradual increase of q''_L results in the decrease in ΔT_{sat} for the given q''_T. Throughout the heat fluxes the enhancement in heat transfer is clearly observed at low or moderate heat fluxes. When q''_T >80kW/m^2 the curve for $q''_L \neq$ 0kW/m^2 converges to the curve for the single tube. The tendency of enhancement depends on q''_T and L_o/L. When q''_L =60kW/m^2 and q''_T <40kW/m^2, ΔT_{sat} is high at L_o/L =1/2. However, at $q''_T \geq$ 40kW/m^2, higher ΔT_{sat} is observed at L_o/L =1. The same is true when $q''_L = q''_T$. The major causes are the convective flow at low heat fluxes and the bubble coalescence at high heat fluxes. At q''_T <40kW/m^2, the size of the bubbles is small and there are a relatively small number of bubbles generated from the surface. The bubbles create convective flow and agitate environmental liquid, which is enhancing heat transfer. Therefore, the enhancement is magnified when the many bubbles come from the lower tube like L_o/L =1. As $q''_T \geq$ 40kW/m^2, the more bubbles coming from the lower side tube accelerates the deterioration of heat transfer due to the coalescence of bubbles. For the reason, the result for L_o/L =1/2 shows enhanced heat transfer at higher heat flux regions. Some photos taken at P =47mm are shown in Fig. 4. Lots of bubbles are observed on the overlapped parts of the upper tube.

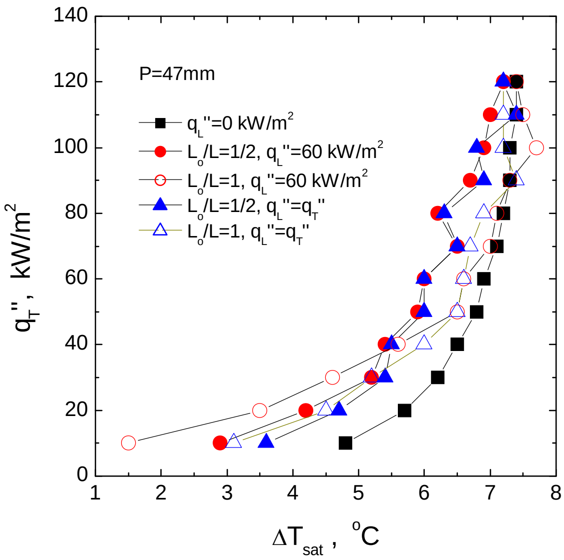
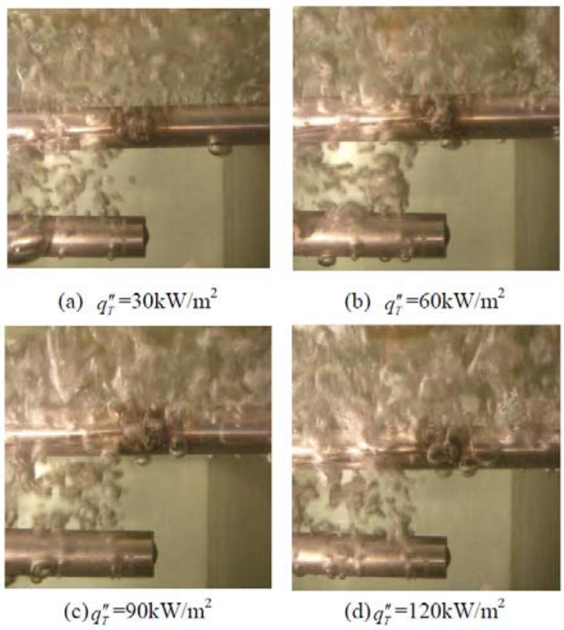


Fig. 3. Plots of q'' versus ΔT_{sat} data for P =47 mm.



(a) q''_T=30kW/m^2 (b) q''_T=60kW/m^2

(c) q''_T=90kW/m^2 (d) q''_T=120kW/m^2

Fig. 4. Photos of boiling on tube surface for L_o/L =3/4 and q''_L =60kW/m^2 (P =47mm).

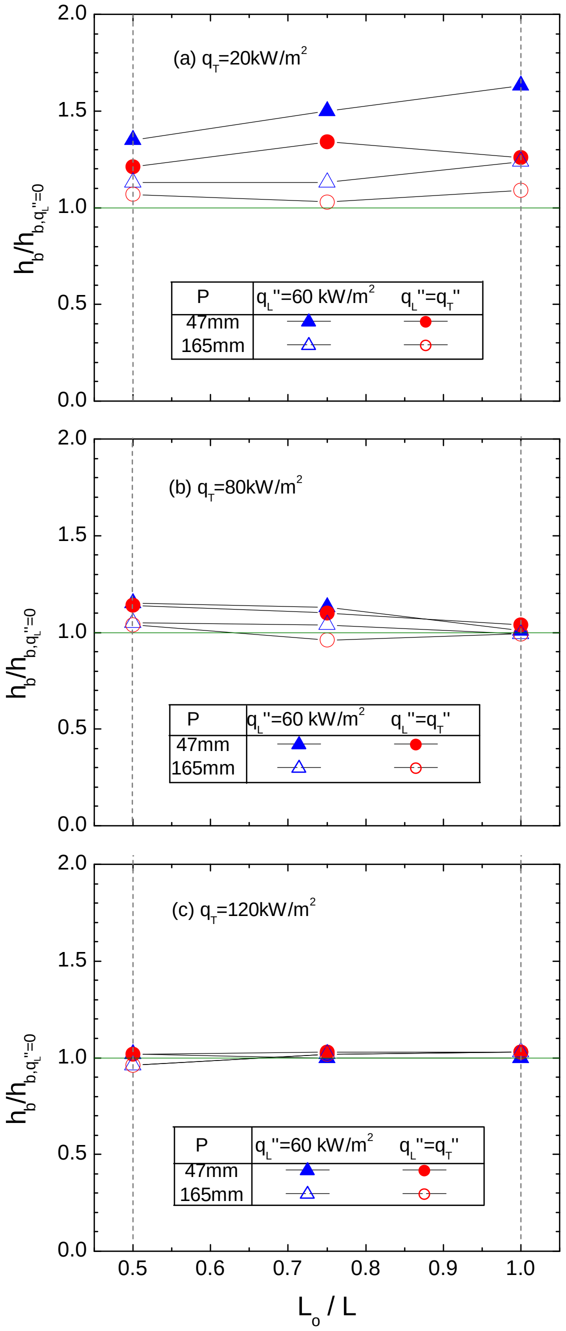


Fig. 5. Plots of $h_b / h_{b,q''_L=0}$ against L_o / L .

To identify the effect of overlap length on heat transfer the ratio of $h_b / h_{b,q''_L=0}$ was obtained for the different q''_L and P as L_o / L varies from 0.5 to 1. When the value of L_o / L is increased the enhancement of heat transfer is observed at q''_T =20kW/m^2. However, $h_b / h_{b,q''_L=0}$ is decreased as L_o / L is increased at q''_T =80kW/m^2. The increase in heat transfer is obvious when the value of q''_L =60kW/m^2 and P =47mm at q''_T =20kW/m^2. Throughout the overlap lengths the enhancement in heat transfer is magnified when P =47mm. However, the effect of the overlap length on heat transfer becomes negligible as q''_T is increased higher than 80 kW/m^2.

The convective flow generated by the lower tube 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. This tendency is clearly observed as the value of L_o / L increases. When the heat flux is increased much more bubbles are generating due to the increase of the nucleation sites. The bubbles become coalescing with the nearby bubbles. This prevents the access of the liquid to the surface and deteriorates heat transfer. Therefore, the decrease of $h_b / h_{b,q''_L=0}$ is observed as L_o / L increases.

4. Conclusions

An experimental study was performed to investigate the combined effects of an overlap length and the heat flux of the lower side tube on pool boiling heat transfer of a tube bundle. The overlap length was varied from 1/2 to 1.0 of the heated tube. Throughout the overlap lengths, the enhancement in heat transfer is magnified as the pitch is smaller and q''_T is at low heat fluxes. The heat transfer is enhanced as L_o / L increases when q''_T is low. However , the vice versa is true when q''_T is high. The convective flow and liquid agitation enhance heat transfer while the coalescence of the bubbles deteriorates heat transfer.

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