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Enhancement of boiling heat transfer in a 5 × 3 tube bundle

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Abstract

The results of an experimental investigation on nucleate boiling heat transfer in an electrically heated 5 × 3 in-line horizontal tube bundle under pool and low cross-flow conditions of saturated water near atmospheric pressure are presented here. It is observed that the heat transfer coefficient is minimum on bottom row tubes and increases in the upward direction with maximum values on top row tubes. Also, heat transfer coefficient on central column tubes was found to be slightly higher than those on the corresponding side tubes. Further, a Chen-type relation has been used to determine the local boiling heat transfer coefficient on a tube in a heated tube bundle.

Keywords: Boiling heat transfer; Tube bundle; Cross-flow

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1. Introduction

The shell-side nucleate boiling in tube bundle finds application in many industrial heat exchange equipment such as steam generators, flooded evaporators and kettle reboilers used in many power, refrigeration, chemical and petroleum processing systems. Though the phenomena of boiling heat transfer on a single tube has been widely studied, the results obtained for a single tube cannot be directly applied to design multitube boiling equipment. This is because the heat transfer characteristics of a tube in a heated tube bundle are quite different from that of a single tube on account of changed flow field and quality environment due to the upcoming vapour bubbles from lower tubes. Very limited work is available in the literature particularly concerning local (i.e., tube position within the tube bundle) boiling heat transfer coefficient in a heated tube bundles. Bennett et al. [1], Cornwell and Leong [2], Polley et al. [3], Hwang and Yao [4], Hsu et al. [5] and Dowlati et al. [6] are some of the researchers who have analyzed the local heat transfer coefficient in tube bundles under cross-flow conditions. These investigators, however, have used ideal tube bundles with small pitch to tube diameter ratios ($P/d = 1.3$–1.5) and maintained a small gap between the outer tube of the bundle and the channel wall. Assuming uniform distribution of vapour bubbles all over the channel cross-section, heat transfer relations were expressed in terms of void fraction or Martinelli parameter. These relations, however, are not suitable for small sized tube bundle arranged in a large channel as the vapour bubbles in such systems confine to a small fraction of the channel cross-sectional area and accurate prediction of local void fraction in such systems is not an easy task. More efforts are therefore still needed to investigate the local boiling heat transfer in tube bundles under wide range of system and operating parameters so as to understand the boiling phenomena in tube bundles

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Nomenclature

Bo	boiling number
C	column factor
d	tube diameter, m
E	enhancement factor
G	mass flux based on minimum flow cross-section area, kg/m^2 s
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
P	pitch distance (m)
q	heat flux, W/m^2
N_r	row number
Re	Reynolds number
T	temperature, K

Greek symbols

μ	viscosity, Ns/m^2
θ	angular position

Subscripts

fg	phase change
l	liquid
r	row
s	saturation
w	wall

more clearly and also to design these equipment efficiently.

In view of this, an experimental investigation was undertaken to study the local and average boiling heat transfer coefficients in a 5 × 3 in-line horizontal tube bundle arranged in a large channel. The effect of heat flux, mass flux on local and average heat transfer coefficient in a tube bundle has been presented in this paper.

2. Experimental set-up

A schematic diagram of the experimental set-up used in the present work is shown in Fig. 1. The test vessel fabricated out of a stainless steel sheet of 3 mm thickness measured 300 mm × 200 mm × 425 mm. The fluid entered the vessel through a perforated horizontal aluminium plate which facilitated flow uniformity at the entrance to the vessel. One side of the test vessel was fitted with a 250 mm × 250 mm × 25 mm bakelite plate with 20 mm diameter holes drilled at desired locations so that tube bundle of desired geometry is made by fixing the test heaters in it. The fluid entering the test vessel was saturated and its temperature was controlled by a heating element provided in the preheater. Energy to this heating element was regulated with a variable transformer. The test heaters were made of a stainless steel tube (AISI 304) of commercial finish having an outer diameter of 19.05 mm and inner diameter 17.27 mm. Each test heater 245 mm long and with an effective heating length of 190 mm was provided with resistive heating by means of a high alternating current fed to it through

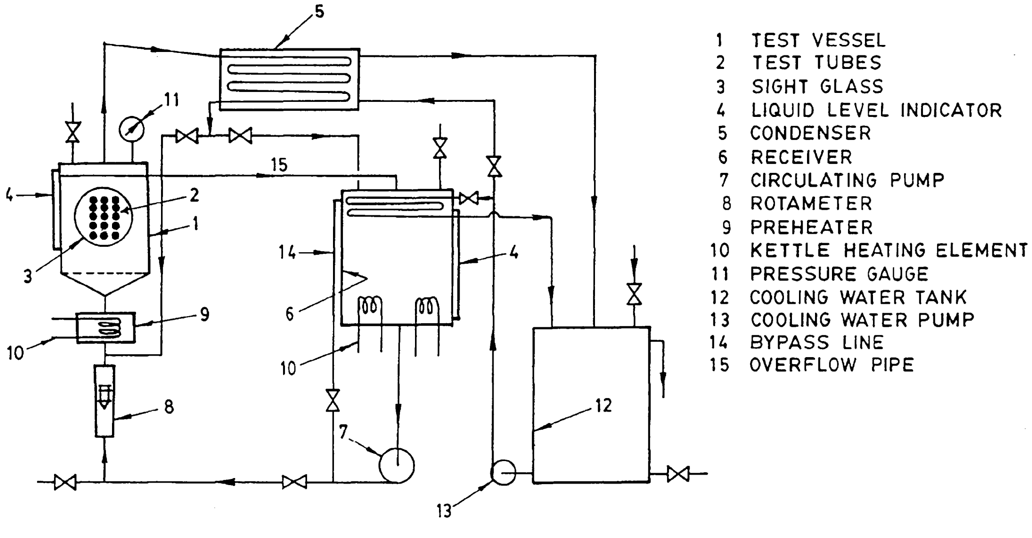

Fig. 1. A schematic diagram of the experimental set-up.

a step down transformer. All tubes of the bundle were connected in series and the amount of current passing through the bundle was controlled through a variable voltage transformer. Power supplied to test heaters was measured with the help of digital voltmeter and digital ammeter with a least count of 0.001 V and 0.1 A, respectively. Eight, 28 BWG copper–constantan thermocouples evenly spaced at 45° intervals around the inner surface wall and midway between the heated length of each tube were used to measure the wall temperatures of the tube. The thermocouples were connected to a 100 channel Data Logging System to record temperature with a sensitivity of 0.01 °C.

The range of system and operating parameters covered in this study is listed below:

Working fluid	distilled water
System pressure	atmospheric
Test vessel cross-section	300 mm × 200 mm
Inlet fluid temperature	saturation temperature
Tube material	stainless steel (AISI 304)
Tube outer diameter	19.05 mm
Tube inner diameter	17.27 mm
Bundle geometry	5 × 3 in-line square tube bundle (*P*/*d* = 1.5)
Heat flux range	10–40 kW/m^2
Mass flux range	0–10 kg/m^2 s

Uncertainties in the experimental data, as estimated through a propagation of error analysis for a typical set of data are:

q, 0.54%; G, 3.62%; T, 2.65%; h, 2.7%; p, 1.23 kPa

The detailed descriptions of the experimental set-up, procedure and calculation method are given in Gupta [7,8].

3. Results and discussion

3.1. Bottom tubes

Heat transfer results obtained for pool and flow boiling for the bottom tubes of central and left columns of 5 × 3 tube bundle are shown in Figs. 2 and 3, respectively. As expected, the heat transfer behaviour on these tubes is similar to that on a single tube heated alone in a channel under similar conditions of heat and mass flux i.e., the heat transfer coefficient increases with the increase of heat flux and cross-flow velocity. The effect of cross-flow velocity is relatively more at low heat flux values and diminishes with the increase of heat flux. This is due to the fact that at higher heat flux values when nucleate boiling is more developed, large number of vapour bubbles are formed all over the tube surface which create a greater degree of turbulence around the tube surface. Contribution of cross-flow velocity in further enhancing the turbulence at the higher range of heat flux may not be so significant.

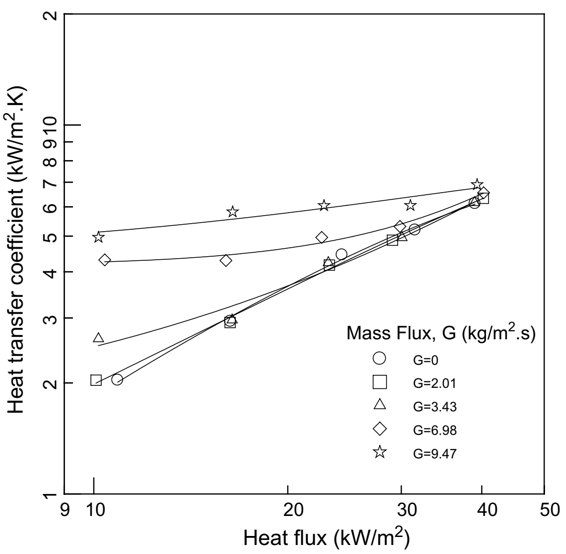

Fig. 2. Heat transfer coefficient on bottom tube of central column.

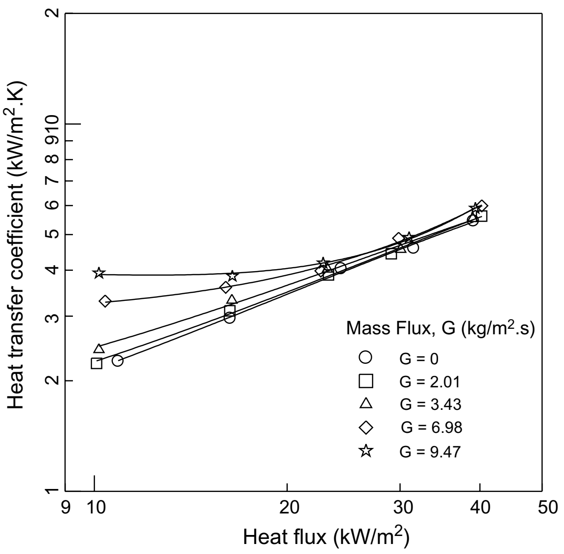

Fig. 3. Heat transfer coefficient on bottom tube of left column.

A comparison of boiling heat transfer on bottom tube of the central column of 5 × 3 tube bundle under pool and maximum cross-flow conditions has been made with that on a single tube and bottom tubes of single column tube bundles of different configurations experimented by Gupta et al. [8]. The results are shown in

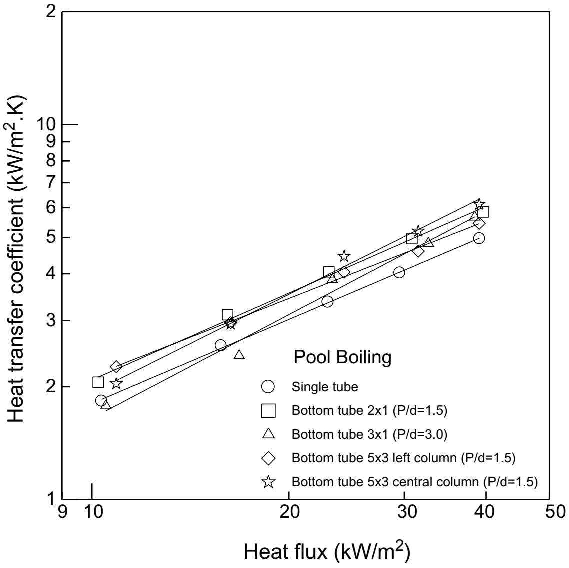

Fig. 4. Comparison of pool boiling heat transfer coefficient on bottom tubes for different tube bundle configurations.

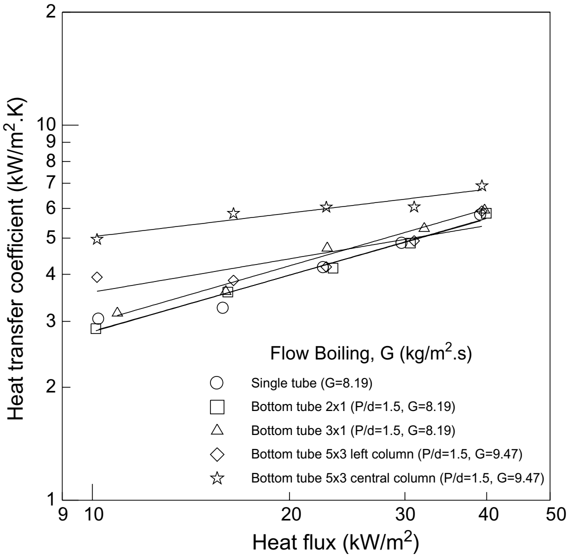

Fig. 5. Comparison of flow boiling heat transfer coefficient on bottom tubes for different tube bundle configurations.

Figs. 4 and 5 for pool and flow boiling conditions, respectively. It is seen that under pool boiling condition the results are almost same in all bundle configurations as compared to that on a single tube. However, in case of maximum flow conditions, the heat transfer coefficients on the bottom tubes of single column tube bundles were nearly the same as that on a single tube, but in case of bottom tube of central column, it is much higher than the bottom tubes of single column tube bundles. The difference however diminishes with an increase in heat flux values. Thus boiling on side column tubes affect the boiling heat transfer coefficient of the bottom tube of central column and the effect is more in flow boiling at low heat flux values.

3.2. Upper tubes

Heat transfer coefficients on the upper tubes of central and left columns of the bundle under pool boiling and maximum cross-flow velocity conditions are shown in Figs. 6–9. It is seen that the heat transfer coefficient increases from the bottom tube towards the top tube. A part of vapour bubbles generated on lower tubes impinges on the surface of upper tubes and enhances turbulence there which in turn enhances the heat transfer coefficient on the upper tubes. Higher the location of a tube in the bundle in flow direction, higher will be the amount of vapour bubbles reaching that tube from bottom and hence higher will be its heat transfer coefficient. Further, it is seen that generally from third tube onwards (from bottom) heat transfer coefficient first increases with increase of heat flux attaining a maximum value and then starts decreasing. As seen from Fig. 6, the maximum heat transfer coefficient corresponds to a heat flux of about 23 kW/m^2 and it is more than seven times higher than the heat transfer coefficient on the bottom tube at the same heat flux. The maxima of heat transfer coefficient is attained at a higher heat flux value in case of lower tubes and the heat flux corresponding to maxima decreases as we move upward in the flow direction. After maxima, heat transfer coefficient starts decreasing and the reason for this may be that at higher

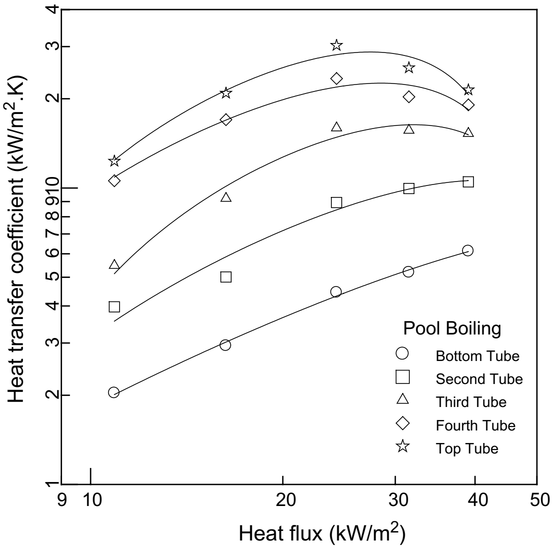

Fig. 6. Heat transfer coefficient on central column tubes in pool boiling.

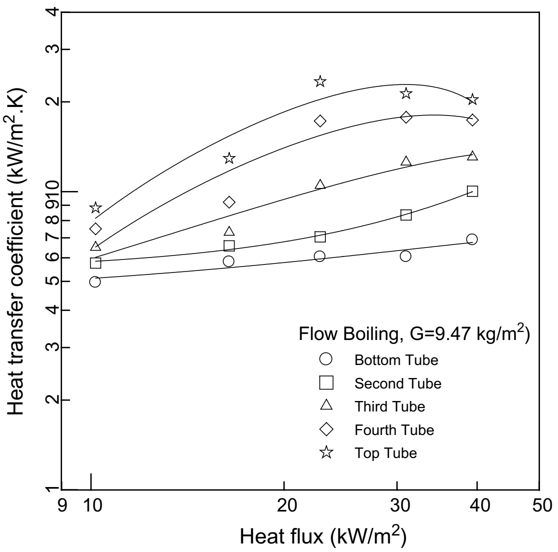

Fig. 7. Heat transfer coefficient on central column tubes in flow boiling.

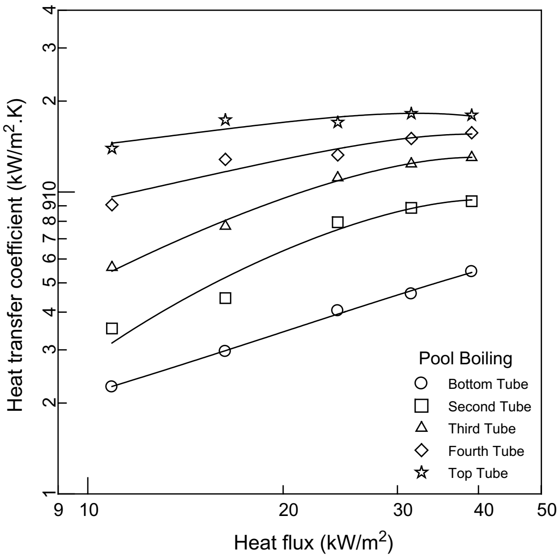

Fig. 8. Heat transfer coefficient on left column tubes in pool boiling.

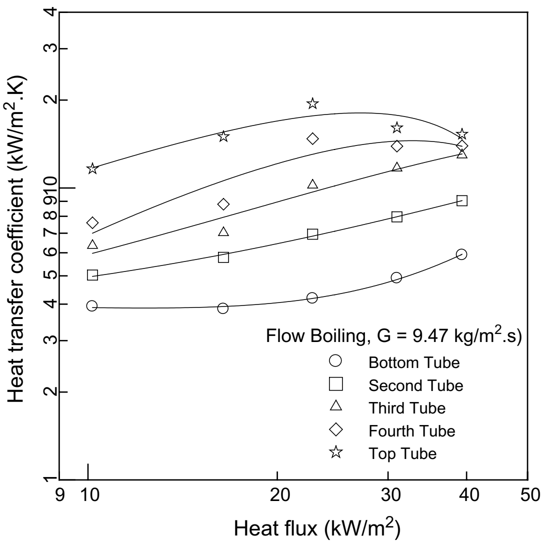

Fig. 9. Heat transfer coefficient on left column tubes in flow boiling.

heat flux values the upper tubes are surrounded too much by vapour bubbles and sufficient amount of liquid from surroundings may not reach these tubes and thus causing a decrease in heat transfer coefficient.

A comparison of boiling heat transfer coefficient on left column and central column tubes shows that heat transfer coefficient in case of central column tubes is higher than that on the corresponding tubes of the left column. The reason is that the central column tubes intercept more vapour bubbles coming up from lower tubes as compared to the side column tubes and thus turbulence on central column tubes is much higher than on the corresponding side column tubes and this results in higher values of heat transfer coefficient on central column tubes.

The effect of cross-flow velocity on heat transfer coefficient of central and side column tubes is shown in Figs. 10–13 for typical heat flux values. It is seen that the effect of cross-flow is significant only at low heat flux values and almost negligible at high heat flux. The reason may be that at high heat flux values the degree of turbulence around the tube surface due to high intensity of nucleation sites on its surface and large amount of vapour bubbles coming up from lower tubes is so intense that the effect of cross-flow in further enhancing this turbulence may be insignificant. Further, it is seen from Figs. 10 and 12 that at low heat flux values the effect of cross-flow velocity is dominant in case of lower tubes and less on upper tubes. Also, heat transfer coefficient on lower tubes increases with the increase of cross-flow velocity and the trend reverses in case of upper tubes. At low heat flux values the nucleation on a tube surface is low and it is further suppressed due to cross-flow velocity and vapour bubbles rising up from lower tubes and impinging on its surface. Heat transfer coefficient on a tube depends upon the contribution from these three factors, i.e., vapour bubbles generated on a tube, the quantity of vapour bubbles coming up from lower tubes and impinging on its surface and the cross-flow velocity. At low heat flux values, maximum amount of vapour bubbles reach the upper tubes in case of pool boiling and the number decreases with an increase of cross-flow velocity. The contribution in the enhancement of heat

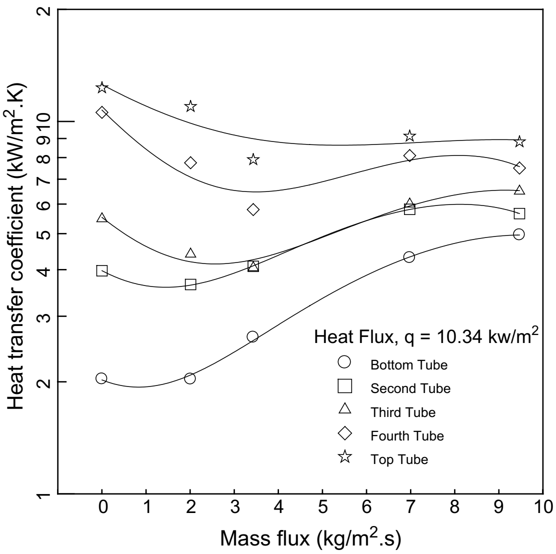

Fig. 10. Effect of cross-flow velocity on heat transfer coefficient of central column tubes at low heat flux.

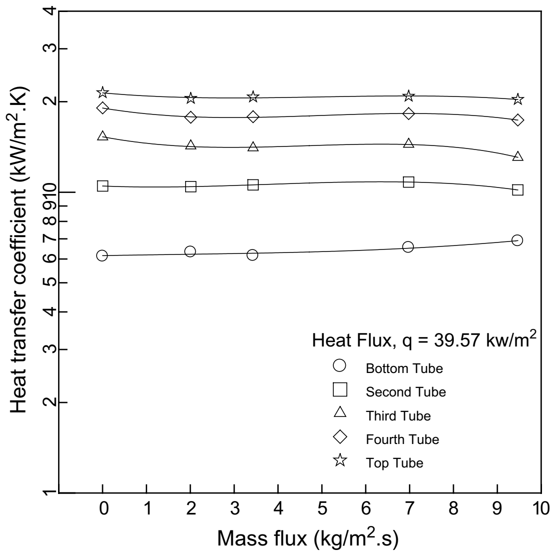

Fig. 11. Effect of cross-flow velocity on heat transfer coefficient of central column tubes at high heat flux.

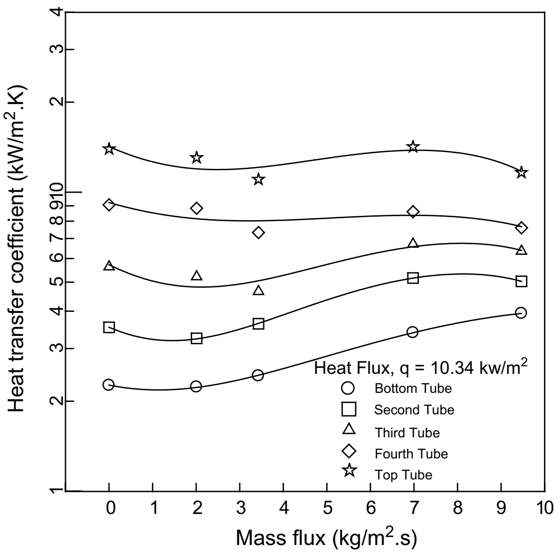

Fig. 12. Effect of cross-flow velocity on heat transfer coefficient of left column tubes at low heat flux.

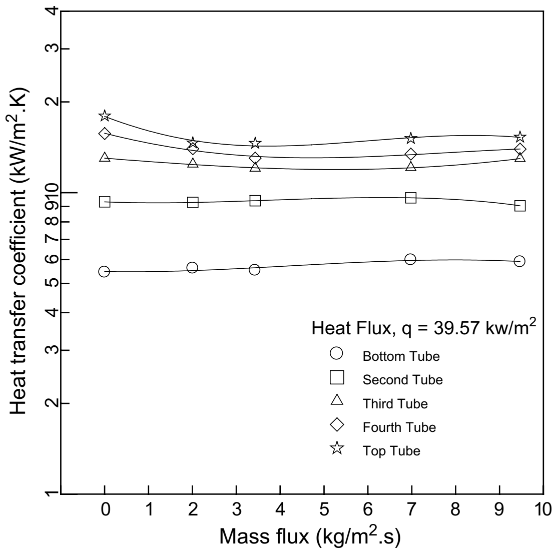

Fig. 13. Effect of cross-flow velocity on heat transfer coefficient of left column tubes at high heat flux.

transfer coefficient on a tube by the vapour bubbles coming up from lower tubes and impinging on its surface is much more than the cross-flow velocity and hence heat transfer coefficient on upper tubes at low heat flux values, decreases with an increase of mass flux as increased mass flux suppresses boiling and less amount of vapour bubbles reaches upper tubes.

The circumferential variation of heat transfer coefficient over the tube surface for typical cases is shown in Figs. 14 and 15. It is found that on all tubes, the maxima and minima of heat transfer coefficient occur near the bottom ($\theta = 0° \pm 45°$) and top position ($\theta = 180° \pm 45°$), respectively for all heat and mass flux values. Also the variation of circumferential heat transfer coefficient was found to be more in case of upper tubes as compared to that on bottom tubes. The variation on the top tube was found to be more at low heat flux values. Maximum variation was 50–60% of the average value in case of top tube and 20–30% in case of the bottom

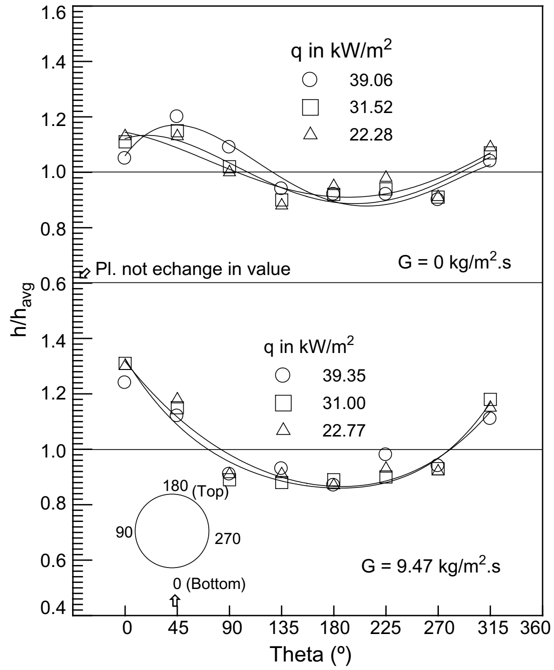

Fig. 14. Circumferential variation of heat transfer coefficient on bottom tube of central column.

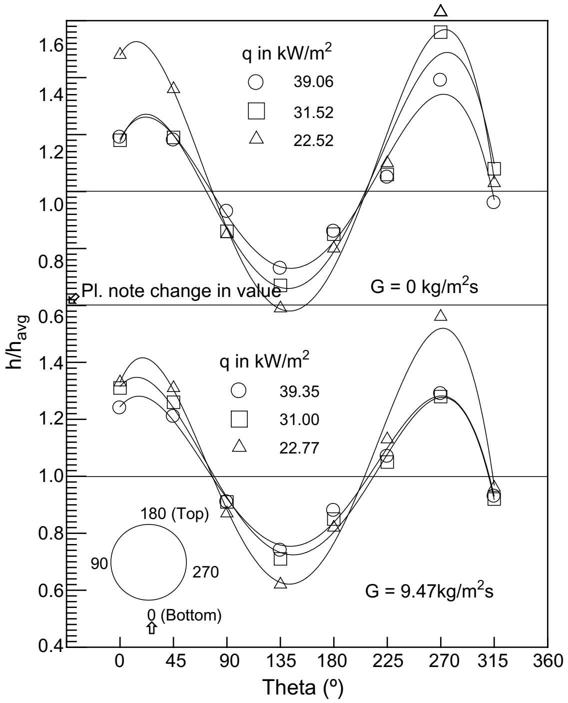

Fig. 15. Circumferential variation of heat transfer coefficient on top tube of central column.

tube. Similar trends of circumferential variation of heat transfer coefficient were found in case of central and side column tubes.

3.3. Tube bundle heat transfer

The tube bundle average heat transfer coefficient of the 5×3 tube bundle has been compared with the bundle heat transfer coefficients of single column tube bundles of different configurations and a single tube of Gupta et al. [8] in Figs. 16 and 17 for typical conditions of pool and maximum cross-flow conditions, respectively. It is seen that the bundle average heat transfer coefficient in case of 5×3 is much higher than that on a single column tube bundles of different configurations. Thus boiling on tubes of side columns helps in enhancing the average bundle heat transfer coefficient substantially. The maximum average bundle heat transfer coefficient in 5×3 tube bundle was about five times higher when compared to the heat transfer coefficient on a single tube under pool boiling condition at a heat flux of about 25 kW/m^2. Further, in all tube bundle configurations, the average bundle heat transfer coefficient was found to increases with the increase of heat flux. In case of 5×3 tube bundle, the rate of increase of average bundle heat transfer coefficient decreases with heat flux. The effect of cross-flow velocity is significant only at low heat flux values and disappears at high heat flux values.

The pitch distance between the tubes also affect the average bundle heat transfer coefficient. The effect of pitch distance, as shown in Figs. 16 and 17, is more pronounced in case of pool boiling and the bundle heat

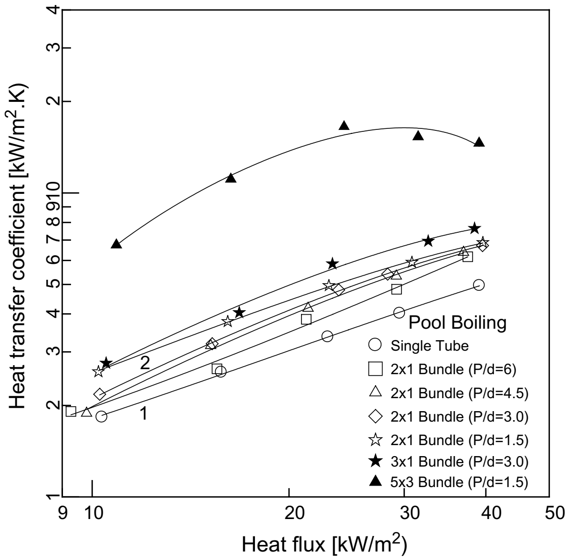

Fig. 16. Average bundle heat transfer coefficient in pool boiling.

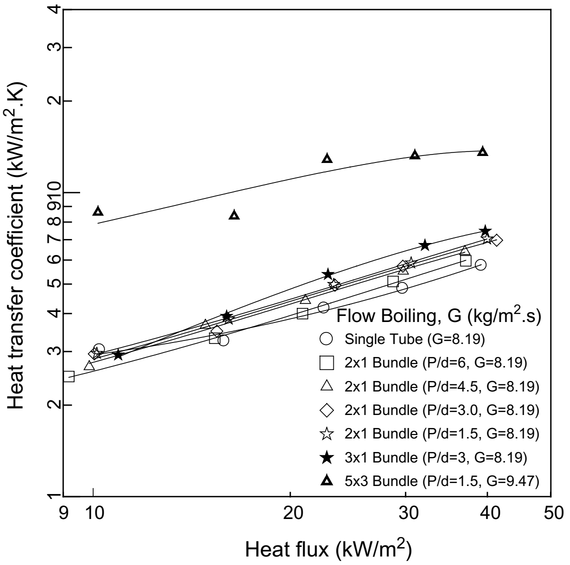

Fig. 17. Average bundle heat transfer coefficient in flow boiling.

transfer coefficient increases as the pitch distance decreases. As observed during the experiment, the vapour bubbles plume diverges as it moves up and hence at lower pitch distance more bubbles from lower tubes impinges on the tube surface and enhances turbulence there. Higher turbulence means higher heat transfer coefficient on that tube.

Increase in the number of tubes in a column also increases the bundle heat transfer coefficient as shown in Figs. 16 and 17. The heat transfer coefficient on a tube increases as we move upward in flow direction and hence an increase in the number of tubes in a column increases the average bundle heat transfer coefficient.

4. Correlation for local heat transfer in tube bundle

A review of literature on boiling heat transfer in tube bundles reveals that most of the researchers [1–6] have predicted the local boiling heat transfer (i.e., heat transfer coefficient on a particular tube of the bundle) in terms of void fraction or Martinelli parameter χ_{tt}. However, these researchers have experimented with ideal tube bundles wherein the distance between the side tube column and channel wall is very small, of the order of half of P/d. In such cases, vapour bubbles are assumed to be distributed almost uniformly throughout the channel cross-section and hence a prediction of void fraction can be made easily. In the present experimental work a row of the tube bundle occupies a small fraction of the channel cross-section. It is only 28.6% in case of a 5×3 tube bundle and 9.5% in case of single column tube bundles. Hence the vapour bubbles generated, in the present investigation, are not distributed uniformly throughout the channel cross-section but are confined mostly to the central region of the channel and hence a correct prediction of void fraction in the present case is not possible.

In view of the above, a simple Chen-type [9] relation as given under has been developed for predicting local heat transfer coefficient for a 5×3 in-line tube bundle and single column tube bundles of different configurations

$$h = h_{\text{mic}} + Eh_{\text{l}} \tag{1}$$

where h_{mic}, the microconvective component relates to heat transfer associated with the bubble nucleation and growth, and Eh_{l} represents the convective heat transfer associated with the bulk movement of vapour and liquid. E, the enhancement factor accounts for the enhancement of the single phase liquid convective heat transfer coefficient on a single tube under cross-flow condition.

To evaluate the microconvective term of forced convection boiling, as suggested by Bennett et al. [1], the most valid pool boiling correlation in terms of the wall superheat, $\Delta T_{\text{s}} = T_{\text{w}} - T_{\text{s}}$, was identified based on the experimental pool boiling results on single tube arranged alone in the channel and is given as

$$h_{\text{PNB}} = 13.035(T_{\text{w}} - T_{\text{s}})^{2.881} \tag{2}$$

The expression for h_{mic} of Eq. (1) is then written by replacing the term ΔT_{s} ($= T_{\text{w}} - T_{\text{s}}$) by ΔT_{e}, the effective wall superheat. Hence h_{mic} may be written as

$$h_{\text{mic}} = 13.035(\Delta T_{\text{e}})^{2.881} \tag{3}$$

ΔT_{e} is evaluated using the expression developed by Bennet et al. [1] as given below

$$\frac{\Delta T_{\text{e}}}{\Delta T_{\text{s}}} = \frac{k_{\text{l}}}{(Eh_{\text{l}})X_0}\left[1 - \text{e}^{-(Eh_{\text{l}}X_0/k_{\text{l}})}\right] \tag{4}$$

where

$$X_0 = 0.041\left[\frac{g_{\text{c}}\sigma}{g(\rho_{\text{l}} - \rho_{\text{v}})}\right] \tag{5}$$

The value of h_{l}, the liquid phase forced convection heat transfer coefficient, is determined using Whitaker's [10] relation as given below

$$h_{\text{l}} = (k_{\text{l}}/d)(0.4Re_{\text{l}}^{1/2} + 0.06Re_{\text{l}}^{2/3})Pr_{\text{l}}^{0.4}(\mu_{\text{l}}/\mu_{\text{w}})^{0.25} \tag{6}$$

A simple correlation for the enhancement factor, E, has been developed in terms of physical and operating parameters of the system. The enhancement factor depends mainly on the agitation due to vapour bubbles rising up from lower tubes and impinging on the tube under consideration; the density of vapour bubbles depending upon the impressed heat flux, cross-flow velocity, pitch distance and the number of tubes located below it. It

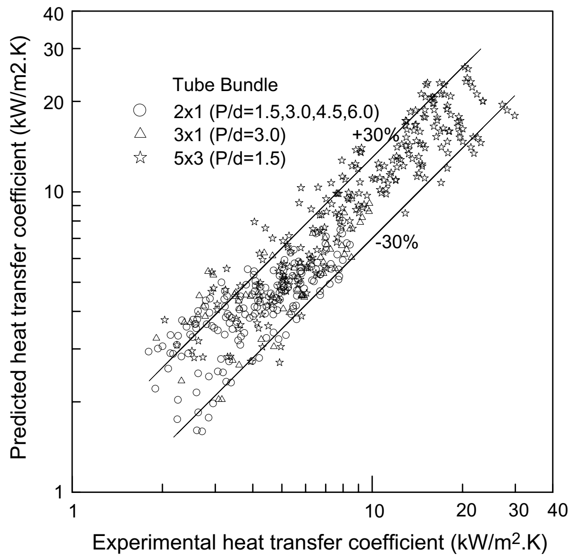

Fig. 18. Experimental vs. predicted local heat transfer coefficient in tube bundles in cross-flow boiling.

can therefore be assumed that E is a function of boiling number, Bo $(=q/h_{\mathrm{fg}}\cdot G)$, pitch to tube diameter ratio, P/d, row number, N_{r} ($N_{\mathrm{r}}=1$ for the bottom tube), and the column factor, C ($C=1$ for single column tube bundles, $C=2$ and 3 for side and central column tubes, respectively in case of 5×3 tube bundle) and is written as

$$E=c(Bo)^{m_1}(P/d)^{m_2}(N_r)^{m_3}(C)^{m_4} \tag{7}$$

Using experimental data and Eqs. (1)–(7) the constant c, and the indices m_1, m_2, m_3 and m_4 were determined and the following expression for the enhancement factor, E is obtained:

$$E=134.24(Bo)^{0.469}(P/d)^{-0.311}(N_r)^{0.946}(C)^{0.304} \tag{8}$$

The values of heat transfer coefficient for tubes were calculated using Eqs. (1)–(8) and compared with those obtained from experimental data as shown in Fig. 18. Experimental data were found to be correlated well, most of the points lie within ±30% and the heat transfer coefficient values have been found to have an average absolute deviation of 20.8%.

5. Conclusions

The following conclusions can be made from the present investigation on boiling heat transfer in tube bundles under pool and cross-flow conditions:

1. Heat transfer characteristics of bottom tubes in a 5×3 tube bundle and single column tube bundles of different configurations were found to be same as that on a single tube heated alone in the channel under similar conditions of heat and mass flux values, i.e., heat transfer coefficient increases with increase of cross-flow velocity and heat flux values. Effect of cross-flow velocity is more at low heat flux values and diminishes with the increase of heat flux.
2. Heat transfer coefficients on bottom tubes under pool boiling condition in 5×3 tube bundle and single column tube bundles were nearly the same as that on a single tube. Under cross-flow condition, heat transfer coefficient on bottom tubes of single column tube bundles was almost same as that on a single tube but a significant enhancement on bottom tubes of 5×3 tube bundle at low heat flux values was observed.
3. Vapour bubbles rising up from lower tubes enhance the turbulence around the upper tubes and this causes a substantial increase in the heat transfer coefficient of upper tubes. Top tube had the maximum enhancement due to cumulative effect of vapour bubbles generated on lower tubes. The maximum heat transfer coefficient on top tube of central column of 5×3 tube bundle was about seven times higher than that on the bottom tube at the same heat flux of 23 $\mathrm{kW/m^2}$ under pool boiling condition.
4. Heat transfer coefficient on central column tubes of 5×3 tube bundle are higher than that on the corresponding tubes of the side columns.
5. Heat transfer coefficient on upper tubes increases first with the increase of heat flux and then decreases; the value of heat flux corresponding to maximum heat transfer coefficient being lowest in case of top tube of the bundle and it increases as we move down from the top tube. The effect of cross-flow velocity on upper tubes of 5×3 tube bundle is significant only at low heat flux values and almost non-existent at high heat flux values.
6. The circumferential variation of heat transfer coefficient was found to be more in case of upper tubes as compared to bottom tube and maxima and minima of heat transfer coefficient occur in all tubes near the bottom and top positions of a tube surface, respectively. Further, variation on top tube is more at low heat flux values.
7. The bundle average heat transfer coefficient in a 5×3 tube bundle is much higher than that in a single column tube bundles of different configurations. The maximum bundle heat transfer coefficient was more than five times higher than the heat transfer coefficient corresponding to a single tube at the same heat flux of 25 $\mathrm{kW/m^2}$. Also, the rate of increase of bundle heat transfer coefficient in a 5×3 tube bundle decreases with an increase of heat flux.
8. The results of single column tube bundles for different configurations showed that the decrease in the pitch to tube diameter ratio, P/d, increases the bundle

heat transfer coefficient. Also, increase in the number of rows in a column increases the bundle heat transfer coefficient.

9. A Chen-type relation has been developed to predict the heat transfer coefficient of a tube in the bundle and the predicted values correlate well with the experimental values.

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