For moderate values of $R_\rho$, the distinguishing feature is the emergence of the multi-layered flow structure. When $R_\rho$ is large, the fluid in the bulk of the container is essentially motionless, and heat transfer is mostly conductive.

The externally-imposed vertical solute gradient is responsible for generating these clearly definable flow regimes. The present findings are in qualitative agreement with the available experimental observations of ref. [9].

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# Effect of spanwise spacing on the heat transfer from an array of protruding elements in forced convection

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## INTRODUCTION

THE COOLING of an array of heat-generating elements mounted in a rectangular channel is an area of immediate interest in electronics packaging research. This problem constitutes a simulation of the flow passages between adjacent circuit boards carrying electronic chips in the CPU of a modern mainframe computer. The heat transfer coefficients as well as the flow patterns within the three-dimensional arrays of chips are not well understood. General surveys of the heat transfer problems in electronics cooling are presented in Chu [1] and Hannemann *et al.* [2], among others.

One topic of interest is the effect of spanwise spacing between elements of each row on the cooling that can be accomplished. Spanwise spacing as a parameter has not been investigated in the literature. Moffat *et al.* [3] studied the heat transfer from two array densities but did not specifically address the influence of spanwise spacing. The first results for liquid cooling of arrays of protruding elements with a range of inter-element spacings in the streamwise and spanwise directions were presented in ref. [4]. The heat transfer coefficient was shown to increase monotonically with an increase in streamwise spacing causing a spread of 35–40% in the heat transfer coefficient for a variation of streamwise spacing over the range of 0.5–6.5 element heights. In comparison, the spread was only 15% for an identical variation in the spanwise spacing between elements.

In the present study, the influence of the spanwise spacing between elements of an array on heat transfer and fluid dynamics is investigated in detail. The elements are mounted on the bottom wall of a horizontal water channel. Flow visualization using laser-sheet-illuminated hydrogen bubbles is used to document the flow patterns within the array.

## EXPERIMENTS

A horizontal Plexiglas water channel with a cross section of 36.6 cm by 6.7 cm and a total length of 180.3 cm was used for the experiments. The height of the channel $H$ was varied over 1.2, 1.9, 2.7, and 3.6 element heights. A schematic of the flow loop is shown in Fig. 1. A detailed description of the experimental facility and procedures is provided in ref. [4].

The bottom wall of the channel is equipped with two detachable hatches. The smaller upstream hatch holds a 25 $\mu$m nichrome wire strung spanwise to generate hydrogen

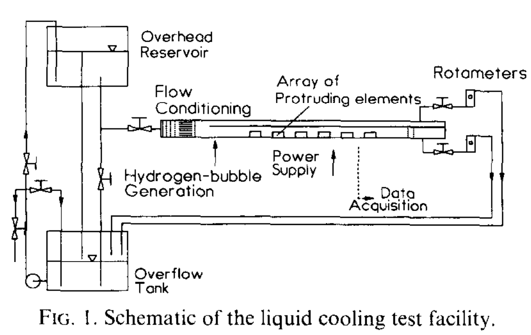


FIG. 1. Schematic of the liquid cooling test facility.

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## NOMENCLATURE

- $A$ active surface area of heated element (16.77 $cm^2$)
- $B$ element height
- $C_d$ drag coefficient
- $C_{d0}$ drag coefficient at $H/B = 1.2$
- $h$ heat transfer coefficient
- $H$ channel height
- $LS$ streamwise spacing between elements
- $P_{s,d}$ downstream static pressure
- $P_{s,u}$ upstream static pressure
- $R$ heater resistance
- $Re_a$ array Reynolds number, $U_a B/\nu$
- $Re_H$ channel-height-based Reynolds number, $U_m H/\nu$
- $SS$ spanwise spacing between elements
- $T_h$ element temperature
- $T_m$ liquid temperature
- $U_a$ array velocity
- $U_m$ mean inlet velocity
- $V$ voltage applied to heater.

Greek symbols

- $\nu$ kinematic viscosity
- $\rho$ density.

bubbles in the flow. The larger hatch is 31.5 cm wide and 45.7 cm long with an array of 30 protruding elements mounted in six spanwise rows of five elements each. The elements are 2.54 cm by 2.54 cm in planform cross section and 1 cm high. All but one of the 30 elements were made from Plexiglas. A single heated copper element was placed in the central column of the fifth row so as to locate it in the fully developed region of the flow. The spanwise spacing ($SS$) between elements was varied through 0.5, 2.2, and 6.5 element heights ($B$), yielding $SS/B = 0.5$, 2.2, and 6.5. Only three elements could be accommodated in each row at the largest spanwise spacing of $SS/B = 6.5$. The streamwise spacing ($LS$) between elements of the array was held constant at 2.54 cm ($LS/B = 2.2$). Temperature measurements were taken for each element spacing over a range of flow rates spanning the laminar and turbulent regimes, and at three of the four channel heights.

The heated element is instrumented with a thermocouple and operated at a specified constant heat flux. The element was assumed to be isothermal and the Plexiglas substrate was treated as being adiabatic in the calculation of the heat transfer coefficient according to the expression

$$h = (V^2/R)/[A(T_h - T_m)] \tag{1}$$

where $V$ is the voltage applied, $R$ the resistance of the heater, $T_h$ the element temperature, and $T_m$ the liquid temperature. The active surface area of each element, $A$, consists of the top surface and the sides. Substrate conduction loss, conduction through the thermocouple and heater lead wires, and radiation heat loss were estimated to constitute a total of less than 1.3% of the heater output. A detailed uncertainty analysis revealed uncertainties in the heat transfer coefficients obtained in this study to be within $\pm 4\%$.

The definition of the array Reynolds number $Re_a$ used in the presentation of results of this study is described in ref. [4] and is given by the expression

$$Re_a = U_a B/\nu \tag{2}$$

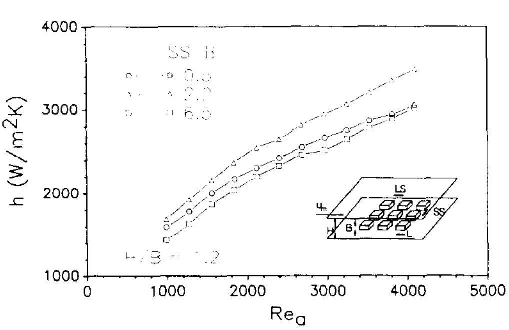



FIG. 2. Effect of spanwise spacing ($SS/B$) on heat transfer coefficient, $H/B = 1.2$.

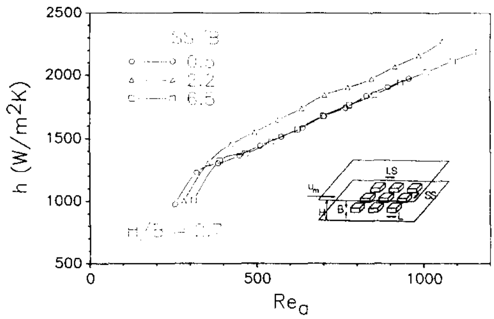



FIG. 3. Effect of spanwise spacing ($SS/B$) on heat transfer coefficient, $H/B = 2.7$.

where $\nu$ is the kinematic viscosity of the liquid. The fraction of the incoming fluid that actually flows through the array has a velocity $U_a$ (array velocity) and is defined as

$$U_a = U_m (C_d/C_{d0})^{1/2} \tag{3}$$

where $C_{d0}$ is the drag coefficient at the lowest channel height and $U_m$ is the mean-inlet velocity. The drag coefficient, $C_d$, is defined as

$$C_d = (P_{s,u} - P_{s,d})/(1/2 \rho U_m^2). \tag{4}$$

The numerator in equation (4) is the difference between the static pressures upstream and downstream of the array, and represents the form drag encountered by the flow passing through the array (neglecting skin friction).

## RESULTS AND DISCUSSION

Heat transfer coefficients are presented as a function of array Reynolds number at channel heights of $H/B = 1.2$, 2.7, and 3.6, respectively, in Figs. 2–4, each for $SS/B = 6.5$, 2.2,

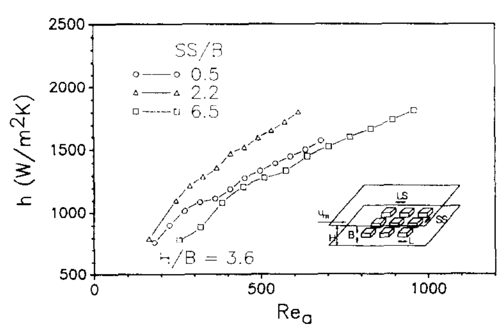



FIG. 4. Effect of spanwise spacing ($SS/B$) on heat transfer coefficient, $H/B = 3.6$.

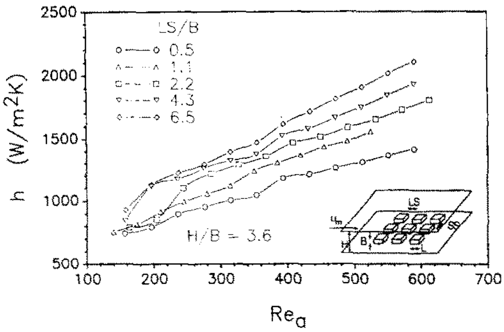



FIG. 5. Effect of streamwise spacing ($LS/B$) on heat transfer coefficient, $H/B = 3.6$.

and 0.6. The spanwise spacing $SS$ and the channel height $H$ are non-dimensionalized using the element height $B$ in the presentation of results. The heat transfer coefficient increases with an increase in Reynolds number as expected. In all the curves, the intermediate spacing ($SS/B = 2.2$) yields higher heat transfer coefficients than the largest and smallest spacings ($SS/B = 6.5$ and 0.5). The pressure drop across the array is much smaller at $H/B = 3.6$ than at the lower channel heights, especially at $SS/B = 6.5$. Uncertainties in the measurement of pressure drop under these conditions account for the observed scatter in the data of Fig. 4, especially at the lower Reynolds numbers.

An examination of Figs. 2–4 shows that the variation of the heat transfer coefficient with spanwise spacing is not monotonic. This is in contrast to the effect of streamwise spacing as discussed in ref. [4], where the heat transfer coefficient increased monotonically with increasing streamwise spacing at all channel heights. To illustrate this contrast, heat transfer coefficients at a channel height of $H/B = 3.6$ are plotted against the array Reynolds number in Fig. 5 for streamwise spacings of $LS/B = 6.5$, 4.3, 2.2, 1.1, and 0.5 (constant $SS/B = 2.2$).

The effect of spanwise spacing on the heat transfer coefficient can be explained by the following mechanisms, proposed based on flow visualization. The extent of the cooling that can be accomplished with any given array configuration depends on the relative heat-transfer contributions of the bypass flow traversing the gap between the elements and the top wall, the flow between columns of elements, and the wakes generated by elements, which in turn depend on the spanwise spacing as discussed below.

Flow visualization results shown in Fig. 6 at a representative channel height of $H/B = 3.6$ for a *channel-height-based* Reynolds number ($U_m H/\nu$) of 3450 illustrate the effect of changing the spanwise spacing through 6.5, 2.2, and 0.5 element heights. Flow is from right to left in these results. The top surfaces of the elements are painted black. The vertical patches of shadow seen in the photographs are caused by obstruction of the illuminating sheet of light by the elements, and do not represent any flow features. At $SS/B = 6.5$ (Fig. 6(a)), the separated shear layers from the sides of each column of elements are seen to extend into the gaps between columns to a distance of about one element height in the spanwise direction. There is little interaction between the wakes from neighboring columns of elements. When the spanwise spacing is reduced to $SS/B = 2.2$ (Fig. 6(b)), wakes from neighboring columns appear to interact strongly with each other. The bypass flow and the flow between columns can penetrate the recirculation regions at this spanwise spacing resulting in enhanced mixing in the recirculation zones and hence, in greater cooling. As the spanwise spacing is further reduced to $SS/B = 0.5$ (Fig. 6(c)), however, each row of elements approximates a transverse rib and the recirculation regions with heated fluid behind the elements remain isolated, giving rise to low heat transfer rates. The resistance offered to the flow by these 'ribs' increases the bypass flow and little penetration of the array is noticed.

The smallest spacing of $SS/B = 0.5$ yields higher heat transfer coefficients than $SS/B = 6.5$ at $H/B = 1.2$ (Fig. 2). This can be explained as follows. The absence of a significant bypass path forces the approaching flow to traverse primarily through the gaps between columns of elements at this channel height, as revealed by flow visualization. Consequently, at this lowest channel height, the cooling of the elements has a greater contribution from the flow in the gaps between columns than from the bypass flow above the tops of the elements. In view of this, the greater penetration of the flow into the gaps between elements at $H/B = 1.2$ has an enhancing effect on heat transfer.

It may be concluded that the *interactions* of separated shear layers and wakes from the neighboring elements have an enhancing effect on heat transfer and mixing. However, the existence of a peak at $SS/B = 2.2$ in the variation of heat

(a)

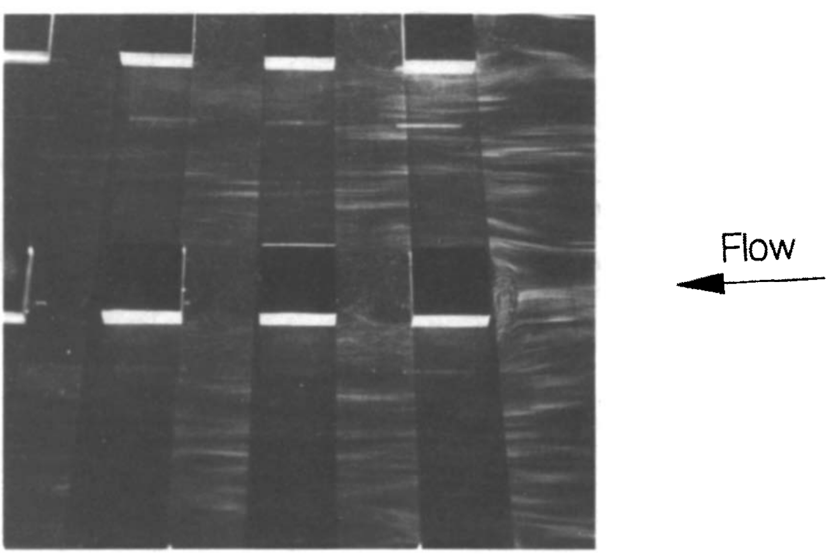
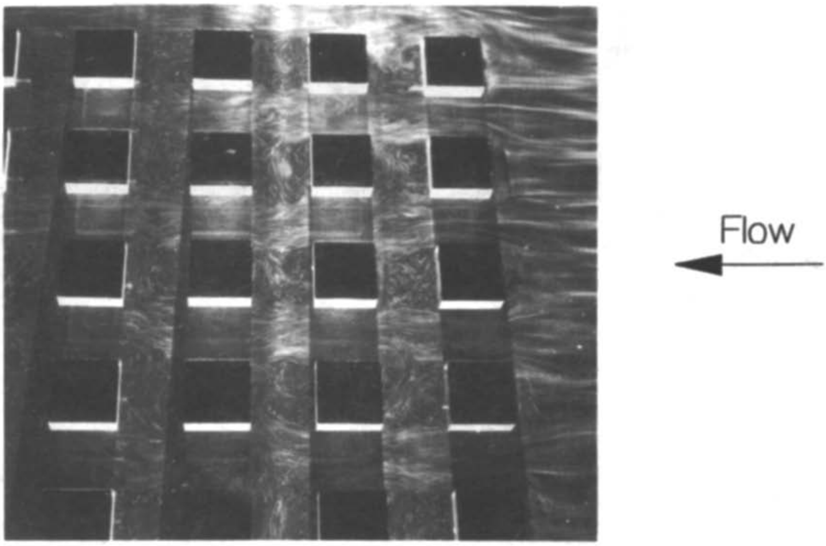
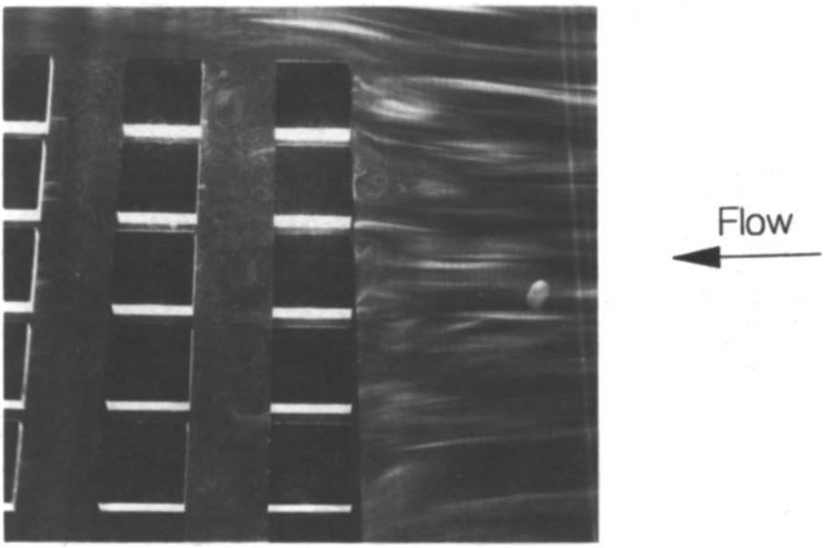



FIG. 6(a).




(b)




(c)

FIG. 6. Plan view of flow through the array, $H/B = 3.6$, $Re_H = 3450$: (a) $SS/B = 6.5$; (b) $SS/B = 2.2$; (c) $SS/B = 0.5$.

transfer coefficient with spanwise spacing implies that the heat transfer enhancement resulting from increased spanwise spacing has an upper limit at an $SS/B$ of around 2.2. On the other hand, when the spanwise spacing is smaller than $SS/B = 2.2$, there is a decreased penetration of the recirculation regions by the flow between columns and the bypass flow, causing lower heat transfer coefficients. Thus there appears to be an optimum spacing for maximum heat transfer when the separated shear layers and wakes generated at the side walls of neighboring elements fill the gaps and are able to interact with each other. For the parameters of this study, the intermediate spacing of approximately two element heights (one element width) was seen to yield maximum heat transfer. The non-monotonic variation of the heat transfer coefficient with spanwise spacing is in contrast to the previously established effect of streamwise spacing on heat transfer.

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