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# CONVECTIVE HEAT TRANSFER RESPONSE TO HEIGHT DIFFERENCES IN AN ARRAY OF BLOCK-LIKE ELECTRONIC COMPONENTS

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## NOMENCLATURE

| | |
|---|---|
| $D$ | diffusion coefficient |
| $H$ | channel height, Fig. 1 |
| $H_c$ | clearance height, Fig. 1 |
| $h$ | module height, Fig. 1 |
| $K$ | per-module mass transfer coefficient at monitored module |
| $L$ | side of square module, Fig. 1 |
| $Nu$ | per-module Nusselt number |
| $Pr$ | Prandtl number |
| $Re$ | Reynolds number, $\dot{w}/\mu W$ |
| $S$ | intermodule gap, Fig. 1 |
| $Sc$ | Schmidt number |
| $Sh$ | Sherwood number at monitored module, $KL/D$ |
| $Sh^*$ | fully developed Sherwood number for the uniform basic array |
| $V$ | characteristic velocity defined by equation (8) |
| $W$ | spanwise width of array |
| $\dot{w}$ | rate of airflow. |

Greek symbols

| | |
|---|---|
| $\mu$ | viscosity |
| $\rho$ | density. |

Subscripts

| | |
|---|---|
| 0.7 | pertains to $Pr = 0.7$ |
| 2.5 | pertains to $Sc = 2.5$. |

## INTRODUCTION

A COMMONLY encountered heat transfer problem in electronic equipment is the cooling of an array of heat-generating, block-like modules. A schematic diagram portraying a representative portion of such an array is shown in the upper part of Fig. 1. In practice, the array is deployed along one wall of a parallel-walled channel as shown in the lower part of Fig. 1.

The heat transfer characteristics of an array of modules of uniform height were investigated experimentally in ref. [1]. In the present experiments, account is taken of the occasional presence of modules whose height differs from that of the modules which make up the basic array. Such an odd-size module is shown in Fig. 1.

The work reported here is results-oriented and employs the apparatus (with suitable modifications), the measurement techniques, and the data reduction procedures of ref. [1]. Therefore, these aspects of the work need not be described here since they are adequately covered in ref. [1]. Rather, the description of the problem will be focused on the geometry of the arrays to be investigated, with particular emphasis on the deployment of the odd-size modules. The results will be presented in ratio form which compares the per-module heat transfer in the presence of odd-size modules with that for the basic array without odd-size modules.

## DESCRIPTION OF THE ARRAYS

The basic array consists of square modules of uniform height given by

$$h/H = 3/8, \tag{1}$$

with module side length $L/H = 1$ and intermodule gap $S/L = 1/4$. Five different modifications of the basic array were employed to investigate the effect of the presence of odd-size modules. These modified array configurations are depicted in Figs. 2 and 3. Configurations I–III are shown in Fig. 2, with configurations IV and V shown in Fig. 3. Each illustrated configuration is a plan view of the portion of the array which contains the odd-size modules. The complete array is not shown, but it extends upstream, downstream, and to the sides to an extent sufficient to eliminate end effects in the illustrated portion of the array. That is, if the odd-size modules were not present, fully developed flow would prevail in that part of the array.

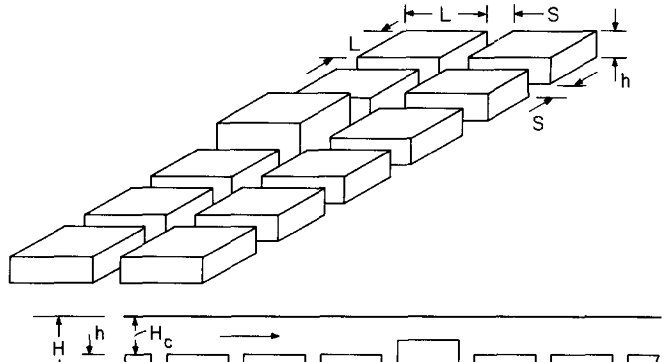


FIG. 1. Upper diagram: pictorial drawing of a representative portion of an array of block-like modules. Lower diagram: side view of the module array deployed along one wall of a parallel-walled channel.

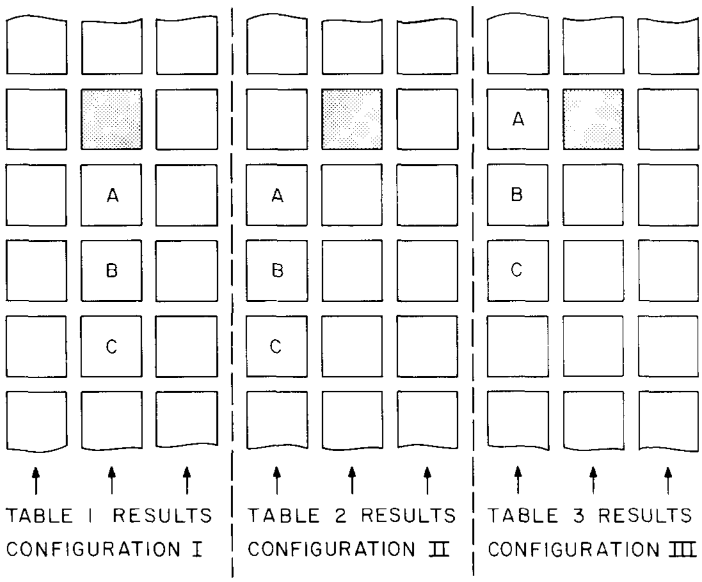


FIG. 2. Layouts of configurations I–III (see Tables 1–3 for detailed specifications).

The modules which make up the array configurations shown in Figs. 2 and 3 are of three types. Those modules which are shown as unmarked open squares belong to the basic array and are characterized by the height $h/H = 3/8$. The squares marked with letters such as A, B,..., or with letter-number combinations A1, A2,..., are locations where there *may* be an odd-size module which creates a hydrodynamic disturbance. At each marked location, the height of the module is equal to one of the following

$$h/H = 0, 1/4, 3/8, 5/8. \quad (2)$$

The case of $h/H = 0$ corresponds to the absence of a module, while a $h/H = 3/8$ module is a member of the basic array. Specification of the actual heights of the marked modules will be made in Tables 1–5 that will be described shortly.

In each configuration, there is one module that is shown speckled. This is the module at which heat transfer coefficients are measured and recorded. Throughout the remainder of the paper, it will be designated as the monitored module. Monitored modules having heights

$$h/H = 1/4, 3/8, 5/8 \quad (3)$$

will be considered.

To further clarify the specifics of the investigated configurations, a more detailed description may be given for one of them, say, configuration I. The layout of this configuration is shown on the LHS of Fig. 2, and the numerical specifications of the heights of modules A, B, and C and of the monitored module are listed in Table 1.

Information about the odd-size modules at positions A, B, and C is provided on the LHS of Table 1. The first entry 'none' is meant to indicate that there are no odd-size modules at A, B, or C, that is, the modules at A, B, and C are those of the basic array ($h/H = 3/8$). The next three entries pertain to $h/H = 0$, i.e. to missing modules. Among these, the specification '$h/H = 0$ A, B, C' means that there are no modules at A or B or C. The next specification '$h/H = 0$ A, B' indicates absent modules at locations A and B, while module C is of the basic array ($h/H = 3/8$). The meaning of '$h/H = 0$ A' is that there is an absent module at A and basic $h/H = 3/8$ modules at B and C.

This same format is used for the $h/H = 1/4$ and $5/8$ odd-size modules. Thus, for example, '1/4 A, B' means $h/H = 1/4$ modules at A and B and a $h/H = 3/8$ module at C. From these examples, it is seen that among the set A, B, C, if the module height $h/H$ is not specified, it is understood to be that of the basic array ($h/H = 3/8$).

The height of the monitored module is specified in the heading on the RHS of Table 1. As seen there, the monitored module was sequenced through heights $h/H = 1/4$, 3/8, and 5/8 for each of the specified arrangements of modules A, B, and C.

Configurations I, II, and III (all depicted in Fig. 2) pertain to odd-size modules aligned either directly upstream or at the upstream side of the monitored module. The geometric specification of configurations II and III follows a format identical to that already described for configuration I (see Tables 2 and 3) and no further elaboration is needed.

Attention may now be turned to configurations IV and V, respectively shown in Fig. 3 and specified in Tables 4 and 5. For configuration IV, Table 4 indicates that an odd-size module is situated at *one* among the five locations A, B, C, D, E,

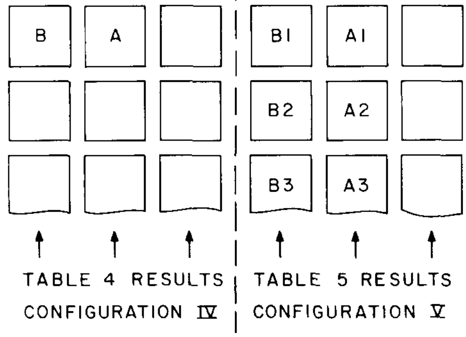


FIG. 3. Layouts of configurations IV and V (see Tables 4 and 5 for detailed specifications).

Table 1. Values of $Sh/Sh^*$ at monitored module of height $h/H$ in presence of odd-size modules of configuration I (Fig. 2)

| | Odd-size modules | | | $Sh/Sh^*$ | |
|---|---|---|---|---|---|
| $Re$ | $h/H$ | Positions $h/H =$ | 1/4 | 3/8 | 5/8 |
| 2000 | None | | 1.06 | 1.00 | 1.80 |
| | 0 | A, B, C | 1.62 | 1.71 | 1.94 |
| | 0 | A, B | 1.57 | 1.62 | 1.89 |
| | 0 | A | 1.53 | 1.46 | 1.80 |
| | 1/4 | A, B, C | 1.26 | 1.41 | 1.91 |
| | 1/4 | A, B | 1.26 | 1.41 | 1.92 |
| | 1/4 | A | 1.26 | 1.33 | 1.86 |
| | 5/8 | A, B, C | 1.33 | 1.28 | 1.14 |
| | 5/8 | A, B | 1.35 | 1.32 | 1.18 |
| | 5/8 | A | 1.43 | 1.38 | 1.36 |
| 7000 | None | | 1.26 | 1.00 | 1.79 |
| | 0 | A, B, C | 1.64 | 1.66 | 1.85 |
| | 0 | A, B | 1.54 | 1.58 | 1.83 |
| | 0 | A | 1.43 | 1.36 | 1.76 |
| | 1/4 | A, B, C | 1.16 | 1.52 | 1.81 |
| | 1/4 | A, B | 1.16 | 1.48 | 1.83 |
| | 1/4 | A | 1.20 | 1.39 | 1.81 |
| | 5/8 | A, B, C | 1.19 | 1.18 | 1.10 |
| | 5/8 | A, B | 1.19 | 1.18 | 1.12 |
| | 5/8 | A | 1.25 | 1.26 | 1.23 |

while at the other four locations the modules are of the basic array ($h/H = 3/8$). For reference purposes, the case of no odd-size modules at A, B, C, D, E (i.e. $h/H = 3/8$ at these locations) is also included in Table 4. For each position of the odd-size module, the monitored module is varied through heights $h/H = 1/4$, 3/8, and 5/8.

Configuration V is characterized by a single missing module which may be positioned at any one of the locations $A2^-, \ldots, A10, B2^-, \ldots$. The locations designated with a minus superscript are downstream of the monitored module, while the other locations are upstream. Aside from the site of the missing module, all other marked locations are populated with modules of the basic array. The heights of the monitored module are $h/H = 1/4$, 3/8, and 5/8.

Table 2. Values of $Sh/Sh^*$ at monitored module of height $h/H$ in presence of odd-size modules of configuration II (Fig. 2)

| | Odd-size modules | | | $Sh/Sh^*$ | |
|---|---|---|---|---|---|
| $Re$ | $h/H$ | Positions $h/H =$ | 1/4 | 3/8 | 5/8 |
| 2000 | None | | 1.06 | 1.00 | 1.80 |
| | 0 | A, B, C | 1.50 | 1.34 | 1.75 |
| | 0 | A, B | 1.38 | 1.25 | 1.76 |
| | 0 | A | 1.11 | 1.08 | 1.77 |
| | 1/4 | A, B, C | 1.17 | 1.10 | 1.79 |
| | 1/4 | A, B | 1.12 | 1.07 | 1.79 |
| | 1/4 | A | 1.06 | 1.01 | 1.77 |
| | 5/8 | A, B, C | 1.35 | 1.18 | 1.91 |
| | 5/8 | A, B | 1.35 | 1.21 | 1.92 |
| | 5/8 | A | 1.35 | 1.18 | 1.89 |
| 7000 | None | | 1.26 | 1.00 | 1.79 |
| | 0 | A, B, C | 1.47 | 1.26 | 1.77 |
| | 0 | A, B | 1.43 | 1.26 | 1.78 |
| | 0 | A | 1.30 | 1.13 | 1.76 |
| | 1/4 | A, B, C | 1.30 | 1.14 | 1.78 |
| | 1/4 | A, B | 1.28 | 1.14 | 1.76 |
| | 1/4 | A | 1.26 | 1.10 | 1.76 |
| | 5/8 | A, B, C | 1.33 | 1.12 | 1.84 |
| | 5/8 | A, B | 1.34 | 1.13 | 1.83 |
| | 5/8 | A | 1.37 | 1.16 | 1.87 |

Table 3. Values of $Sh/Sh^*$ at monitored module of height $h/H$ in presence of odd-size modules of configuration III (Fig. 2)

| | Odd-size modules | | | $Sh/Sh^*$ | |
|---|---|---|---|---|---|
| $Re$ | $h/H$ | Positions $h/H =$ | 1/4 | 3/8 | 5/8 |
| 2000 | None | | 1.06 | 1.00 | 1.80 |
| | 0 | A, B, C | 1.20 | 1.24 | 1.78 |
| | 0 | A, B | 1.05 | 1.09 | 1.81 |
| | 0 | A | 1.04 | 1.07 | 1.80 |
| | 1/4 | A, B, C | 1.05 | 1.09 | 1.79 |
| | 1/4 | A, B | 1.03 | 1.05 | 1.80 |
| | 1/4 | A | 0.95 | 0.98 | 1.80 |
| | 5/8 | A, B, C | 1.34 | 1.18 | 1.90 |
| | 5/8 | A, B | 1.35 | 1.22 | 1.87 |
| | 5/8 | A | 1.45 | 1.36 | 1.82 |
| 7000 | None | | 1.26 | 1.00 | 1.79 |
| | 0 | A, B, C | 1.28 | 1.21 | 1.77 |
| | 0 | A, B | 1.27 | 1.14 | 1.79 |
| | 0 | A | 1.21 | 1.10 | 1.79 |
| | 1/4 | A, B, C | 1.18 | 1.09 | 1.74 |
| | 1/4 | A, B | 1.17 | 1.09 | 1.75 |
| | 1/4 | A | 1.16 | 1.01 | 1.79 |
| | 5/8 | A, B, C | 1.32 | 1.11 | 1.85 |
| | 5/8 | A, B | 1.35 | 1.15 | 1.84 |
| | 5/8 | A | 1.51 | 1.38 | 1.83 |

## THE EXPERIMENTS

The actual experiments were performed using the naphthalene sublimation technique, the application of which to the module array is described in ref. [1]. Only the monitored module was made of naphthalene and participated directly in the mass transfer process. The other modules in the array were metallic (brass) and served to establish the velocity field.

The per-module mass transfer coefficient $K$ at the monitored module is reported in terms of the Sherwood number $Sh$, which is the mass transfer counterpart of the Nusselt number

$$Sh = KL/D. \tag{4}$$

The Sherwood numbers measured in naphthalene sublimation experiments correspond to a Schmidt number $Sc = 2.5$. By employing the analogy between heat and mass transfer, these results can be transformed to Nusselt numbers applicable to heat transfer in air, for which the Prandtl number $Pr$ is 0.7. As shown in ref. [1], the transformation is

$$Nu_{0.7} = 0.632 Sh_{2.5}. \tag{5}$$

A substantial portion of the results will be presented in terms of the ratio $Sh/Sh^*$. The numerator is the monitored-module Sherwood number corresponding to the various modified array configurations. The denominator is the Sherwood number for fully developed flow in the basic array, where all modules, including the monitored module, are of uniform height $h/H = 3/8$. In the ratio, both $Sh$ and $Sh^*$ correspond to the same Reynolds number. Furthermore, in accordance with equation (5)

$$(Nu/Nu^*)_{0.7} = (Sh/Sh^*)_{2.5}, \tag{6}$$

so that the reported Sherwood number ratios should be applicable for heat transfer in air.

The Reynolds number used to parameterize the results is defined as

$$Re = \rho V H_c/\mu, \tag{7}$$

in which $H_c$ is the clearance height shown in the lower part of Fig. 1. Furthermore

$$\rho V = \dot{w}/WH_c, \tag{8}$$

Table 4. Values of $Sh/Sh^*$ at monitored module of height $h/H$ in presence of odd-size modules of configuration IV (Fig. 3)

| | Odd-size modules | | | $Sh/Sh^*$ | | |
|---|---|---|---|---|---|---|
| $Re$ | $h/H$ | Position | $h/H$ = | 1/4 | 3/8 | 5/8 |
| 2000 | None | | | 1.06 | 1.00 | 1.80 |
| | 0 | A | | 1.53 | 1.46 | 1.80 |
| | 0 | B | | 1.11 | 1.08 | 1.77 |
| | 0 | C | | 1.04 | 1.07 | 1.80 |
| | 0 | D | | 1.02 | 1.01 | 1.81 |
| | 0 | E | | 1.03 | 1.08 | 1.83 |
| | 1/4 | A | | 1.26 | 1.33 | 1.86 |
| | 1/4 | B | | 1.06 | 1.01 | 1.77 |
| | 1/4 | C | | 0.95 | 0.98 | 1.83 |
| | 1/4 | D | | 1.02 | 0.96 | 1.81 |
| | 1/4 | E | | 1.03 | 1.04 | 1.79 |
| | 5/8 | A | | 1.43 | 1.38 | 1.36 |
| | 5/8 | B | | 1.35 | 1.18 | 1.89 |
| | 5/8 | C | | 1.45 | 1.36 | 1.82 |
| | 5/8 | D | | 1.18 | 1.15 | 1.80 |
| | 5/8 | E | | 1.16 | 1.22 | 1.74 |
| 7000 | None | | | 1.26 | 1.00 | 1.79 |
| | 0 | A | | 1.43 | 1.36 | 1.77 |
| | 0 | B | | 1.30 | 1.12 | 1.75 |
| | 0 | C | | 1.21 | 1.10 | 1.79 |
| | 0 | D | | 1.23 | 1.02 | 1.79 |
| | 0 | E | | 1.17 | 1.07 | 1.79 |
| | 1/4 | A | | 1.20 | 1.39 | 1.81 |
| | 1/4 | B | | 1.26 | 1.10 | 1.76 |
| | 1/4 | C | | 1.16 | 1.01 | 1.79 |
| | 1/4 | D | | 1.21 | 1.01 | 1.78 |
| | 1/4 | E | | 1.17 | 1.03 | 1.76 |
| | 5/8 | A | | 1.25 | 1.26 | 1.23 |
| | 5/8 | B | | 1.37 | 1.16 | 1.87 |
| | 5/8 | C | | 1.51 | 1.38 | 1.83 |
| | 5/8 | D | | 1.31 | 1.19 | 1.88 |
| | 5/8 | E | | 1.25 | 1.21 | 1.74 |

Table 5. Values of $Sh/Sh^*$ at monitored module of height $h/H$ in presence of a missing module (Fig. 3)

| | | $Sh/Sh^*$ | | | | | |
|---|---|---|---|---|---|---|---|
| Missing | $h/H$ = | 1/4 | | 3/8 | | 5/8 | |
| module | $Re$ = | 2000 | 7000 | 2000 | 7000 | 2000 | 7000 |
| None | | 1.06 | 1.26 | 1.00 | 1.00 | 1.80 | 1.79 |
| $A2^-$ | | 1.05 | 1.23 | 0.99 | 1.01 | 1.81 | 1.79 |
| $A1^-$ | | 1.03 | 1.17 | 1.08 | 1.07 | 1.83 | 1.79 |
| A1 | | 1.53 | 1.43 | 1.46 | 1.36 | 1.80 | 1.76 |
| A2 | | 1.38 | 1.30 | 1.21 | 1.08 | 1.81 | 1.76 |
| A3 | | 1.28 | 1.24 | 1.15 | 1.02 | 1.81 | 1.77 |
| A4 | | 1.22 | 1.24 | 1.10 | 1.01 | | |
| A5 | | 1.19 | | 1.08 | | | |
| A6 | | | | 1.06 | | | |
| A8 | | 1.14 | | | | | |
| A10 | | 1.10 | | | | | |
| None | | 1.06 | 1.26 | 1.00 | 1.00 | 1.80 | 1.79 |
| $B2^-$ | | 1.04 | 1.24 | 1.01 | 0.98 | 1.80 | 1.79 |
| $B1^-$ | | 1.02 | 1.23 | 1.01 | 1.02 | 1.81 | 1.79 |
| B0 | | 1.04 | 1.21 | 1.07 | 1.10 | 1.80 | 1.79 |
| B1 | | 1.11 | 1.30 | 1.08 | 1.13 | 1.77 | 1.76 |
| B2 | | 1.08 | 1.30 | 1.06 | 1.06 | 1.81 | 1.78 |
| B3 | | | 1.26 | 1.05 | 1.02 | | |

where $\dot{w}$ is the rate of airflow and $W$ is the spanwise width of the array. The combination of equations (7) and (8) yields

$$Re = \dot{w}/\mu W. \quad (9)$$

Equation (9), taken together with the fact that the spanwise width $W$ was the same in both the modified and basic arrays, shows that the Reynolds number serves as a dimensionless airflow rate. Since the Reynolds numbers for the modified arrays were matched to those of the basic array, the airflow rates were, therefore, also matched.

## RESULTS AND DISCUSSION

The first set of results pertains to the case where there is only one module whose height differs from that of the uniform basic array. Sherwood numbers were measured at that module and are plotted in Fig. 4 as a function of the Reynolds number. The plotted results correspond to $h/H$ values of 1/4, 3/8, and 5/8 at the monitored module. The data for the $h/H = 3/8$ monitored module serve as a baseline, since this module height is equal to that of the other modules in the basic array.

The Sherwood numbers at the monitored module for both $h/H = 1/4$ and 5/8 are higher than the baseline Sherwood numbers, indicating that enhancement occurs both when the monitored module is taller and shorter than the modules of the basic array. The mechanism by which the enhancement occurs in the two cases is quite different. For a tall module, the enhancement is caused by direct impingement of the airflow on the portions of the module which protrude above the level of the basic array. On the other hand, the enhancement at a short module is due to the recirculation zone which occupies the cavity in the basic array which is created by the presence of the module. The different Reynolds number dependences of the results for the tall and short modules reflect the aforementioned differences in the factors which cause the enhancement.

The extent of the Sherwood number enhancement at the $h/H = 5/8$ module relative to the baseline ($h/H = 3/8$) module is a nearly uniform 80% over the investigated range of Reynolds numbers. For the $h/H = 1/4$ module, the enhancement increases from a modest 6% at $Re = 2000$ to a more substantial 26% at $Re = 7000$.

Attention is now turned to the results for the various modified array configurations that are conveyed in Tables 1–5. As discussed earlier in the paper, the LHS of each table, in columns headed by either 'odd-size module(s)' or 'missing module', describes the alterations that were made in the basic

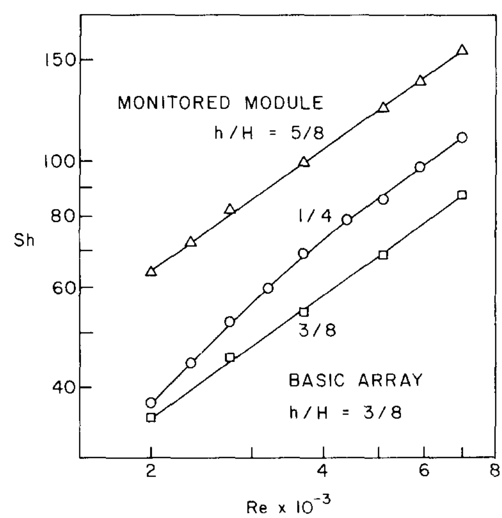


FIG. 4. Sherwood numbers at the monitored module when all other modules are those of the uniform basic array.

array at locations other than at the monitored module. The height of the monitored module is specified in the column headings under which the $Sh/Sh^*$ values are listed. Each table contains results for $Re = 2000$ and 7000. The $Sh^*$ values corresponding to these Reynolds numbers are 35.34 and 87.15, respectively.

When appraising the numerical values of $Sh/Sh^*$ listed in Tables 1–5, there are two frames of reference which appear to be appropriate. The first of these is the deviation of $Sh/Sh^*$ from unity. That deviation indicates whether the collective modifications of the basic array, including modifications at the monitored module and at locations other than the monitored module, are enhancing or degrading for heat transfer. A careful examination of Tables 1–5 reveals that almost without exception, $Sh/Sh^* > 1$. When it is considered that the geometric modifications included both increases and decreases in module height both at and other than at the monitored module, and also included missing modules, the generality of the $Sh/Sh^* > 1$ finding is quite remarkable. On this basis, it would not be unreasonable to state that, in general, geometrical alterations of a uniform array of modules enhance heat transfer.

In the second interpretation of the results, attention is focused on alterations of the array at locations other than at the monitored module and on how these alterations affect $Sh/Sh^*$ at the monitored module. This approach involves a two-step comparison. First, the $Sh/Sh^*$ value at a monitored module of specified height $h/H$ is noted for the case in which all the other modules are those of the basic array. This information is given in the first row of each table, to the right of the entry 'none' under the headings 'odd-size module(s)' or 'missing module'. Then, for the same monitored module (i.e. same $h/H$), the $Sh/Sh^*$ value is noted corresponding to an alteration of the array as designated under any of the aforementioned headings. If the second value of $Sh/Sh^*$ is greater than the first, then the array alterations are enhancing; the opposite relationship indicates degradation.

From the standpoint of this interpretation, certain generalizations can be made from an inspection of the tables. The Sherwood number at a tall monitored module ($h/H = 5/8$) is quite insensitive (i.e. $Sh/Sh^* \sim 1.8$) to alterations in the basic array except when one or more tall modules are positioned directly upstream of it. In that case, the screening action of the upstream modules reduces the Sherwood number. When the height of the monitored module is that of the basic array ($h/H = 3/8$), alterations in the array are generally enhancing (i.e. $Sh/Sh^* > 1$). In the case of a low monitored module ($h/H = 1/4$), enhancement or degradation can occur depending on the specifics of the array modifications.

If the tables are examined one-by-one, a host of specific tendencies can be observed, over and above those discussed in the foregoing paragraphs. In this regard, consider, for example, Table 1. Among the issues addressed in this table is the response of $Sh/Sh^*$ at a given monitored module to the number of the odd-size modules that are placed in the array. Aside from the case of the $h/H = 0$ odd-size modules (i.e. missing modules), for which 3–6% variations in $Sh/Sh^*$ occur, it appears that the monitored module is quite insensitive to whether there are two or three odd-size modules directly upstream of it (i.e. positions A, B vs positions A, B, C). In comparing the effect of one vs two odd-size modules, two missing modules are seen to yield higher $Sh/Sh^*$ values than does one missing module, with an opposite trend for the $h/H = 5/8$ odd-size modules. The $h/H = 1/4$ odd-size modules yield a mixed trend.

An appraisal of each of the other tables yields both general and mixed trends, as in the foregoing discussion of Table 1.

## CONCLUDING REMARKS

The objective of the present work was to determine how the per-module heat transfer coefficient for an otherwise uniform array of modules is affected by the occasional presence of odd-size modules or of missing modules. A wide variety of arrangements of odd-size or missing modules was investigated, and the corresponding heat transfer coefficients were ratioed with those for the uniform array. These ratios are presented in tables which convey a large amount of specific information. The main general conclusion of the research is that alterations of module height in an otherwise uniform array of modules enhance heat transfer.

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1. E. M. Sparrow, J. E. Neithammer and A. Chaboki, Heat transfer and pressure drop characteristics of arrays of rectangular modules encountered in electronic equipment, *Int. J. Heat Mass Transfer* **25**, 961–973 (1982).