Int. J. Heat Mass Transfer. Vol. 34, No. 9, pp. 2431–2433, 1991
Printed in Great Britain

0017-9310/91 $3.00+0.00
© 1991 Pergamon Press plc

Enhancement of single phase convective heat transfer from protruding elements using vortex generators

S. V. GARIMELLA† and P. A. EIBECK

Department of Mechanical Engineering, University of California at Berkeley, Berkeley, CA 94720, U.S.A.

(*Received* 13 *April* 1990 *and in final form* 26 *November* 1990)

INTRODUCTION

AN EXPERIMENTAL study was undertaken to investigate the extent of heat transfer enhancement obtained by introducing vortex generators upstream of an array of heated protruding elements. The elements are mounted on the bottom wall of a horizontal water channel. This situation simulates the flow passages between adjacent circuit boards carrying electronic chips in the CPU of a modern mainframe computer.

It was shown in ref. [1] that staggering the elements of an array leads to increases in the heat transfer of 10–40% relative to the inline array. But this is accompanied by a corresponding increase in pressure drop of 20–110% over the inline array. In the present study, enhancement in heat transfer from the inline array is brought about by installing a row of vortex generators upstream of the array. A large number of experimental studies in the literature (for instance, Fiebig *et al.* [2], Russell *et al.* [3], and Zhang *et al.* [4]) have addressed the heat transfer enhancement brought about by vortex generators, in various configurations and applications. A detailed review is beyond the scope of this note.

In one of the few previous studies involving heat transfer enhancement in arrays of obstacles, Chou and Lee [5] used vortex generators in an attempt to reduce temperature non-uniformities in air flow over heated elements. The vortex generator used in that study was a rectangular barrier mounted on the trailing edge of the preceding element. Introduction of this barrier was found not only to reduce the maximum temperature of the downstream element but also to reduce temperature variations over the element surface.

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 can be 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. [1].

The bottom wall of the channel is equipped with a detachable hatch. An array of 30 heated copper elements is mounted on this hatch 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. The spacing between elements of the array in the streamwise and spanwise directions is 2.54 cm. Each element is instrumented with a thermocouple. All heaters are connected in parallel across a pair of bus bars and operated at the same voltage. The heaters were operated at a specified constant heat flux.

Each 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

$$h = (V^2/R)/[A(T_h - T_m)]$$

where V is the voltage applied, R the resistance of each heater, T_h the element temperature, and T_m the bulk-mean liquid temperature. The active surface area of each element, A, consists of the top surface and the sides. Substrate conduction losses, 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 ±4%. Two static pressure taps are located in the bottom wall to measure pressure drop across the array. Uncertainties in the measurement of pressure drop were estimated to be $\pm 0.5\ \mathrm{N\ m^{-2}}$.

Heat transfer enhancement was investigated by installing one vortex generator upstream of each column of elements at a distance equal to the streamwise spacing between elements (2.54 cm). The vortex generator used (see Fig. 2) was a half-delta wing placed at an angle of attack of 20° to the flow direction with the trailing edge of the wing tip aligned with the centerline of each column of elements. The triangle

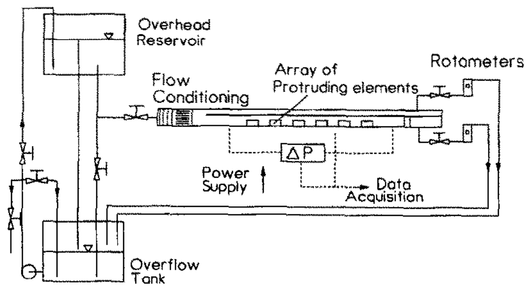

FIG. 1. Schematic of the liquid cooling test facility.

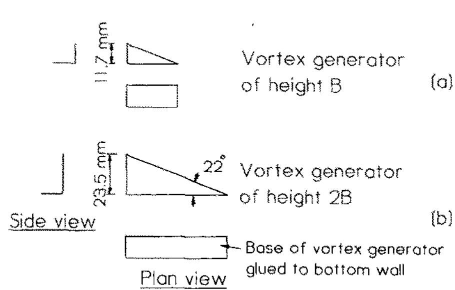

FIG. 2. Geometry of the vortex generators.

†Current address: Department of Mechanical Engineering, University of Wisconsin, Milwaukee, WI 53201, U.S.A.

NOMENCLATURE

A	active surface area of heated element ($16.77\ cm^2$)	R	heater resistance
B	element height	Re_H	channel Reynolds number, ($U_m H/\nu$)
h	heat transfer coefficient based on bulk-mean liquid temperature	T_h	element temperature
H	channel height	T_m	bulk-mean liquid temperature
		U_m	mean-inlet velocity
		V	voltage applied to heater.

describes an angle of 22° between the base and hypotenuse. Two sets of vortex generators were used, with heights equal to one and two element heights (B and $2B$). Temperature and pressure drop measurements were obtained over a range of flow rates spanning the laminar and turbulent regimes.

RESULTS AND DISCUSSION

Row-averaged heat transfer coefficients for the array with all elements heated and vortex generators installed upstream are presented as a function of channel Reynolds number (Re_H) in Figs. 3–5. The percentage enhancement in heat transfer coefficient due to vortex generators, relative to the configuration with no vortex generators, is plotted in these figures. For the case of vortex-generator height equal to the element height (B), shown in Fig. 3 with a channel height of $H/B = 3.6$, all rows except the first show similar trends. The enhancement in the first row exhibits a smaller dependence on Reynolds number, with a mild peak in enhancement of only 15% at $Re_H = 2000$, and a gradual decrease to approximately 5% for $Re_H > 3000$. For the other rows, the heat transfer enhancement is a strong function of Reynolds number, with a peak occurring at $Re_H = 1700$, and negligible enhancement (within experimental uncertainty) for $Re_H > 2700$. The enhancement is greatest for the second row, with a peak level of 30%. The magnitude of peak enhancement decreases with increasing row number.

The enhancement due to vortex generators of the same height (B) show a similar dependence on row number at a different channel height of $H/B = 1.9$, as shown in Fig. 4. The peak enhancement is almost 22% for the second row and decreases with increasing row number. The greatest enhancement for each row occurs in the Reynolds-number range of 800–900. As observed in Fig. 3 for $H/B = 3.6$, the enhancement in the first row exhibits a slightly different trend compared to the other rows even at the smaller H/B of 1.9 (Fig. 4). The peak enhancement of approximately 15% in the first row occurs at a Reynolds number of 1000.

Vortex generators of height $2B$ result in greater heat transfer enhancement than those of height B, as illustrated in Fig. 5. The first row exhibits a greater sensitivity to Reynolds number in this case, with a distinct peak in augmentation of 32% at $Re_H = 2200$, and a monotonic decline with increasing Reynolds number. As with the shorter vortex generators, all rows other than the first have a peak enhancement at a lower $Re_H = 1800$, with a maximum peak enhancement of 41% occurring in the second row. The enhancement levels decrease with increasing Reynolds number to reach a constant value of approximately 5% for $Re_H > 3000$. Similar trends were observed for vortex generators of height $2B$ at a different channel height of $H/B = 2.7$, with a peak enhancement in the second row of 26% at $Re_H = 1500$.

The increase in pressure drop across the array (all six rows) due to the introduction of vortex generators was found to be modest. Representative values of pressure drop are shown as a function of Reynolds number in Fig. 6 for a channel height of $H/B = 3.6$. Data are presented for the array with and without vortex generators (height $2B$). There is a slight increase in pressure drop due to the presence of the vortex generators, the average increase for all Reynolds numbers being approximately 7%. Pressure-drop results for Reynolds numbers less than 700 are not included in the figure, since the magnitude of the pressure drop in this range becomes comparable to the uncertainty in measurement.

The low enhancement observed in the first row relative to the other rows is due to the direct impingement of the incoming flow. There are no stagnant fluid pockets in front of the first row and the heat transfer coefficients are much higher than for the rest of the array. Hence, the vortices introduce only a minor improvement in the thermal mixing that the first row experiences. The greatest impact of the vortex generators is on the second and third rows where the vortical motion significantly improves mixing of the outer cool flow with the fluid trapped between the elements. As the row number increases, the decay of the vortices causes a reduction in their effectiveness.

The trends of enhancement with Reynolds number indicate that the vortex generators are most effective in the laminar and transition regimes. It was shown in ref. [1] that transition occurs at an Re_H of approximately 1900 for the

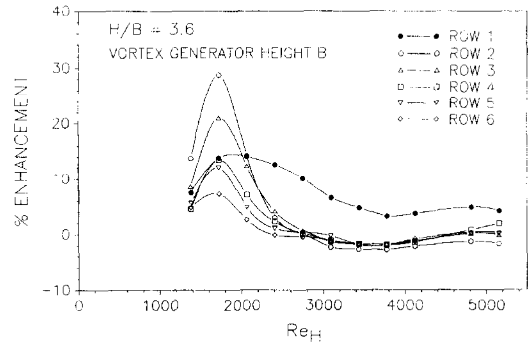

FIG. 3. Heat transfer enhancement with vortex generators of height B, $H/B = 3.6$.

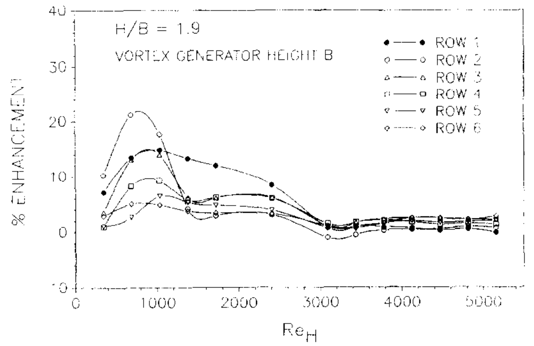

FIG. 4. Heat transfer enhancement with vortex generators of height B, $H/B = 1.9$.

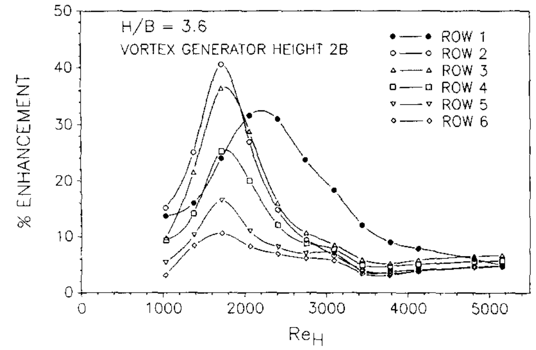

FIG. 5. Heat transfer enhancement with vortex generators of height $2B$, $H/B = 3.6$.

$H/B = 3.6$, and the greatest enhancement is seen to occur in this Reynolds-number range. At the other channel heights with $H/B = 1.9$ and 2.7, transition was recorded at Reynolds numbers of 950 and 1550 [1], and the greatest enhancement is again observed at these Reynolds numbers. It is proposed that the vortices augment heat transfer in this regime through the action of mean, swirling motions as well as by triggering transition to turbulence at a lower Reynolds number. At the higher Reynolds numbers, the high turbulence levels introduce excellent mixing even without vortices present, and hence the vortices introduce only a modest improvement.

The vortex generators that are twice the element height are more effective for heat transfer enhancement than the generators with a height equal to that of the elements. This suggests that the taller vortex generators create vortices that travel in the bypass flow path above the array and hence can survive for a longer distance downstream. The shorter vortex generators, on the other hand, create vortices much closer to the bottom wall and are dissipated by the array. This effect is especially evident at the higher Reynolds numbers where there is negligible enhancement introduced by the shorter vortex generators. The large turbulent motions within the array at higher Reynolds numbers may be responsible for increasing the dissipation rate of the vortices.

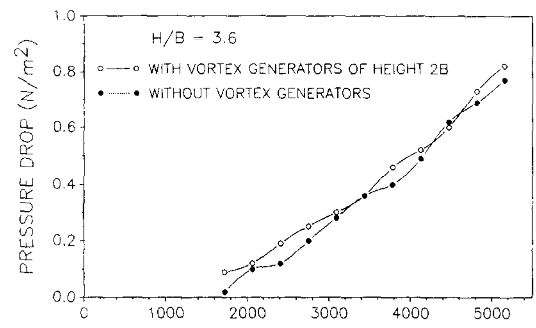

FIG. 6. Pressure drop across the array with and without vortex generators (height $2B$), $H/B = 3.6$.

The occurrence of a peak in the heat transfer enhancement two rows downstream of an implanted barrier and a subsequent drop with increasing row number was reported by Sparrow *et al.* [6] in air. It was also observed that taller barriers yielded greater enhancement. In these respects, the present results using vortex generators are consistent with previous results from implanted barriers.

In summary, vortex generators installed upstream of the array were found to cause the maximum heat transfer enhancement (up to 40%) at the second row of elements. Heat transfer enhancement increased with increasing Reynolds number in the laminar regime, reaching a peak around transition. In the turbulent regime, however, the additional enhancing effect of the vortex generators was lower, of the order of 5%. Taller vortex generators had the greater enhancing effect on heat transfer. Also, the enhancement was greater at the larger channel height. There is only a small increase in pressure drop due to the introduction of the vortex generators, when compared to staggering the elements, but the heat transfer enhancement is also lower and more localized with the vortex generators.

REFERENCES

1. S. V. Garimella and P. A. Eibeck, Heat transfer characteristics of an array of protruding elements in single phase forced convection, *Int. J. Heat Mass Transfer* **33**, 2659–2669 (1990).
2. M. Fiebig, P. Kallweit and N. K. Mitra, Wing type vortex generators for heat transfer enhancement, *Proc. 8th Int. Heat Transfer Conf.*, San Francisco, Vol. 6, pp. 2909–2913 (1986).
3. C. M. B. Russell, T. V. Jones and G. H. Lee, Heat transfer enhancement using vortex generators, *Proc. 7th Int. Heat Transfer Conf.*, Munich, Vol. 3, pp. 283–288 (1982).
4. Zhang, M. Fiebig and N. K. Mitra, Vortex breakdown on heat transfer enhancement in flows between parallel plates, Eurotherm Seminar No. 91, *Heat Transfer in Single Phase Flows*, Bochum, pp. 97–104 (1989).
5. J. H. Chou and J. Lee, Reducing flow non-uniformities in LSI packages by vortex generators, *Proc. Int. Symp. on Cooling Technology for Electronic Equipment*, Hawaii, pp. 583–594 (1987).
6. 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).