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Improving Flow Circulation in Heat Sinks Using Quadrupole Vortices

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In this paper, we show that improved air circulation above a heat sink is possible using thin winglet-type vortex generators that can be passively retrofitted to an existing unit. By mounting these vortex generators on the leading edge of heat sink fins, pairs of counter-rotating vortices are induced within the interfin spacing. The vortices disturb the boundary layers and serve to mix the air in the interfin channel. The devices we have designed are passive and can be added to existing systems using a simple clip-on mechanism. In this study, several designs are experimentally investigated for the purpose of identifying the optimal configuration that will be most conducive to flow enhancement and, therefore, heat transfer augmentation. Using the typical operational range of air velocities for PCs, routers and servers, an experimental simulation of the interfin channel reveals that certain vortex generators, when placed upstream, can outperform others in their ability to fill the channel with pairs of strong vortices. Multiple pairs can also be generated to further accentuate the heat transfer using dual vortex generators. A description of the specific shapes is furnished here along with particulars of the performance study. By control and manipulation of the vortices, our results suggest the possibility of optimizing the generator design. Experimentation was conducted in two phases. The first phase being a study of the ability to generate and control vortices within the fin channel. This aspect was simulated using a Lexan mock-up of the fin channel that permits introduction of glycerin smoke to visualize the shape, size, strength and structure of the vortices. The clear Lexan permitted viewing of the vortices by passing a red planar laser through the apparatus. The second phase involved using the optimization data gained in the first phase to generate vortices in an actual heat sink fitted with thermocouples to measure the temperatures at various points during heating.

I. Introduction

THE MOST cost effective method of cooling electronics has been, to date, the forced convection method that employs a fan and heat sink placed in contact with the processing chip package. This mechanism has served faithfully for decades but now faces the limitation of its usefulness as the heat flux in the new generations of chips continues to increase beyond the standard, built-in, heat sink capabilities. The thermal engineer also recognizes that the addition of liquid or refrigerant-based cooling significantly increases the cost and complexity of the thermal management system.

Fortunately, a flow control mechanism exists that will permit a small, beneficial increase in the heat removal capability of forced convection. This small increase can be sufficient at times to meet the new heat dissipation demands and obviate the need to employ more expensive technologies. How is this possible? By applying the vortex enhancement techniques used in conventional heat exchangers to the airstream passing through a heat sink. This idea is based on the notion that a vortex with its axis parallel to a surface is accompanied by a cooling effect.

How is this accomplished? To start, the fins of a heat sink can be viewed as parallel flat plates forming channels that guide the airflow. Inducement of longitudinal vortices within a channel can promote mixing and mitigate flow stratification and the undesirable formation of thermal isoclines. This paper describes a passive flow control mechanism that stands to enhance the heat transfer from a heat sink mounted on a chip package. The feasibility of this approach will be demonstrated through experimental application of a vortex generator device to a simulated fin channel of a heat sink.

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It is well known that the difference in temperature exhibited by thermal isoclines forms a thermal gradient. The extent of the gradient in the airflow across a heat sink is commensurate with the potential to absorb heat. The thermal destratification of the airflow lends the key to increasing the heat transfer without increasing the volumetric flow rate. Clearly, disruption of both the boundary layers on the fin surfaces and of the thermal gradient can be brought about by the induced vorticity. The corresponding vortical motion helps to circulate the air within the interfin channel, thus transporting chunks of cooler air to the fin surface. The increased thermal gradient at the fin surface translates, of course, into higher rates of heat transfer.

II. Background

Work on understanding vortices and vortex interaction extends back nearly a century, specifically, to Lanchester's experimentation in 1907 which proved that wingtip vortices could intercoil, as predicated by the Helmholtz vortex theorems in 1858 [1-3]. Streamwise vortices have long been known to occur when the flow encounters an object normal to its path in the boundary layer. A three-dimensional surface protuberance will cause the flow to split and flow around the impedance. Sedney inspected a variety of protuberances and presented his findings in 1973, noting that the location and height of the disturbance were the key parameters governing vortex size and shape. He found that the height must be comparable in size to the displacement boundary layer thickness. Furthermore, his longitudinal vortices persisted for a length equivalent to more than 100 boundary layer heights downstream of the disturbance [4]. As the vortices form around the protuberance, a hairpin shape is generated with two parallel, longitudinal, or streamwise, counter-rotating vortices extending downstream as they increase in diameter. The structure, when viewed near a flat plate, is similar to a truncated set of Taylor-Görtler vortices. In 1970, McCormack, Welker and Kelleher published a paper on the heat transfer effects of Taylor-Görtler vortices; this supported the belief that the local heat transfer coefficient could be improved, remarkably, by as much as 190% over flat plates with the addition of induced vortices [5].

Lowering of the chip temperature is typically the goal of thermal management as decreasing the temperature of a component will enhance the component's performance and reliability. Kraus and Bar-Cohen have found that a 2°C increase in chip temperature will reduce a chip's reliability by approximately 10% [6]. If a reduction in the temperature of a chip can be achieved without a reduction in the power input, the chip's life will be extended and the safety margin for power fluctuations will be increased. Limiting the temperature increase in the chip/heat sink assembly by as little as the 2°C cited becomes crucial as the maximum operating temperature is approached. In short, the proposed application may be considered successful if it can help to decrease the chip temperature.

The application of vorticity to a channel flow has been studied in the form of round or oval tube and flat plate fin heat exchangers. The variety of design parameters that influence performance has led to numerous potential vortex generator designs. Generally, these have taken the shape of triangular or rectangular tabs, termed wings or winglets, inclined into the airflow. The effect of varying the parameters has been well described in Fiebig's comprehensive review papers of 1995 [7] and 1998 [8] as well as Jacobi and Shah's 1995 review [9].

Application to a channel flow has been studied in heat exchangers but not extended to the narrow confines of heat sink fin channels [10-32]. Additionally, the placement of vortex generator tabs upstream of a chip without a heat sink or a printed circuit board (PCB) has also been undertaken [33-39]. While researchers have succeeded in generating cooling on PCBs none appears to have applied the concept directly to the heat sink with the intent of inducing vortices within the fin channel itself. In this study, we focus on demonstrating the potential effectiveness of such application.

III. Problem Statement

There is a general agreement that performance of a vortex generator is a function of ambient flow conditions, shape, and geometric characteristics of the environment in which the vortex generator is placed. The extensive body of literature regarding vortex generation contains no consensus as to the optimal configuration for the majority of the incumbent design parameters. The usually mentioned design parameters include the shape, aspect ratio, angle of attack, channel height, thickness, and the position relative to the flow. In terms of the flow conditions, the Reynolds number and flow regime are deemed most important. The geometry of the interfin channel is also critical as it influences the performance through the aspect ratio and length of the channel.

The chief attributes of the vortices of interest are their impact on (i) the spread, (ii) longevity, (iii) strength, (iv) interfin channel fill, (v) stability and (vi) the response time to achieve their maximum development. By evaluation of these key parameters, the optimal design of a vortex generator applied to a heat sink channel may be identified. Optimization of the parameters leads to control and manipulation of the vortices for enhancing their eventual performance. A detailed evaluation of the impact of these parameters will be covered in the subsequent paper on the the optimization of the design.

The optimization framework can be implemented by experimental, numerical and analytical means. This paper discusses the experimental selection of the parameters and their corresponding ranges, their application to the heat sink, and the conditions for evaluation.

IV. Design Parameters

Based on a survey of the literature, it is apparent that the most promising shapes are those of the triangular wings and winglets. In fact, prior research [4,40-43] suggests that equilateral triangular shaped wings will produce stable, paired counter-rotating vortices. All shapes described in the literature are flat. However, no mention is found of alternate triangular shapes that incorporate curvature to the generator or that consider a trapezoidal shape that would induce hairpin vortices or a double-delta shape that mimics jet aircraft wing design. In order to assess the impact of the shape on performance, the (a) flat, (b) trapezoidal, (c) curved, and (d) double delta designs are studied here. These test shapes are shown in Figs. 1a–d.

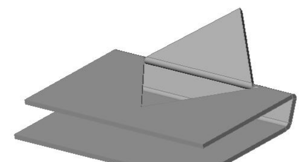
The aspect ratios found in the literature range from 0.8 to 2.0. This ratio compares the square of the base span, "*b*", to the area of the generator, A_{VG} ; it is given by

$$\Lambda_{\mathrm{VG}} = \frac{b_{\mathrm{span}}^2}{A_{\mathrm{VG}}}$$

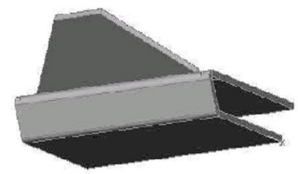
where the subscript "VG" denotes "vortex generator."

At the maximum of 2.0, the base span equates to the height of the generator. This produces an angle between the base span and the leading edge of 63.44°, denoted as α in Fig. 2. For the current application, our tests (below) suggest that the optimal angle for the maximum vortex diameter and spread is 45°, thus requiring an aspect ratio of 4.0 [44]. In turn, this requires the largest area of triangle to fit the space at the entrance to the fin channel. Conceding that the literature leans toward 2.0 as the optimal value, our exploration is conducted at set aspect ratios of 2.0 and 4.0.

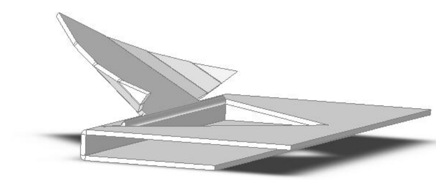
The angle of attack provides the next important optimization parameter as the generator must be inclined into the airflow to induce the largest possible pair of vortices. Here too, our technical survey yields no consensus as to the optimal value. Indeed, the literature exhibits not only variation among researchers as to the most beneficial angle but also variation over time in the papers of individual researchers. Historically, 45° has



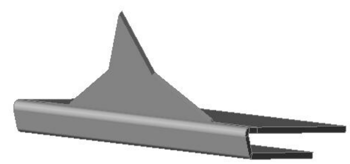
a) Flat triangular design.



b) Trapezoidal design.



c) Curved design.



d) Double delta design.

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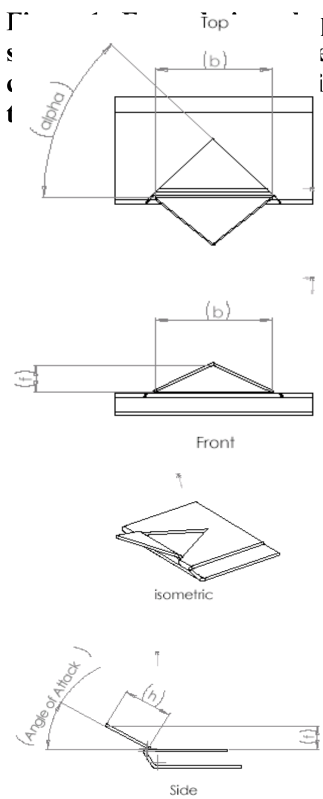


Figure 2. Identification of key geometric design parameters.

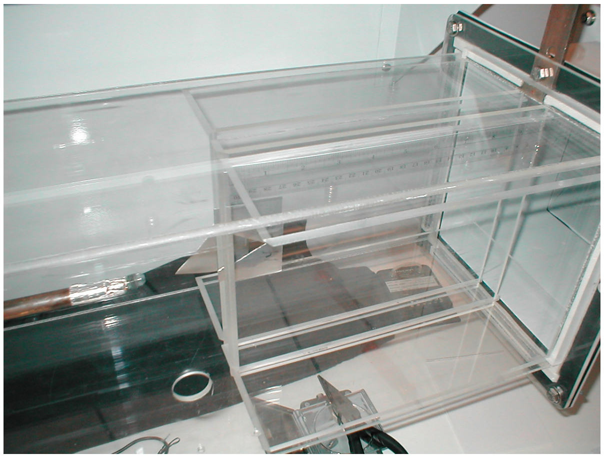


Figure 3. Simulated interfin channel with test vortex generator installed.

Table 1. Simulated channel specifications

Width	1.00"
Height	7.50"
Length	12.00"

been used as the test value. To resolve this point, angles of 30°, 45° and 60° are examined.

The angle of attack also contributes to determination of the channel height at the leading point of the generator. The leading point is the foremost tip of the generator with reference to the airstream. When the generator height, referenced to the leading point, is held fixed, the channel height will vary according to the angle of attack: lower angles of attack produce lower channel heights. To ascertain if there is a contribution to performance from the channel height, three values are examined. The selected cases correspond to ¼, ½ and ¾ of the channel height with respect to the leading point location. The relative measurement locations are given in Fig. 2 where "*f*" denotes the channel height, and "*h*" is the in-plane, generator height.

V. Experimental Procedure

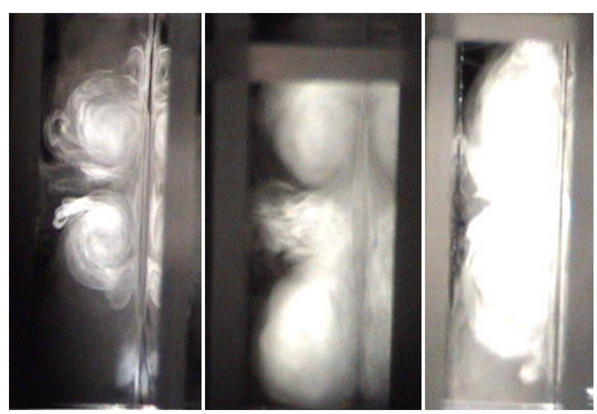
The combinations of selected design parameters give rise to 72 test pieces; these are placed inside a small wind tunnel equipped with a Plexiglas fixture designed to simulate the fin channel of a heat sink. The vortex generator test pieces are individually mounted at the entrance of the simulated fin channel shown in Fig. 3. Corresponding physical dimensions are posted in Table 1. Glycerin smoke is injected upstream of the vortex generator near the leading point. The development of the vortex pair is discernible as it moves through the simulated fin channel.

The developing vortices are viewed in both white light illuminated from below the test section and in red laser light emitted from above. For both cases, the light is introduced in a planar sheet to highlight the cross-sectional structure of the vortex pair. The flow visualization of the structures is analyzed by comparing a number of characteristic parameters including dimensionless comparators of (1) the vortex width-to-height ratio, denoted as ζ; (2) the vortex pair distance-between-dipole-centers-to-span ratio, staged by γ; (3) the percentage comparators of the filled width, indicated by ω; and (4) the critical developing length, shown as κ.

The vortex width-to-height ratio compares the ovality of the vortex pair by relating the interfin vortex width to the vortex height in the channel's longitudinal direction. The distance between dipole centers provides a measure of the spread across the vortex pair; this takes into account the distance spanned between the vortices' outer rims that is usually filled by the common downwash bar. The filled width comparator correlates the interfin channel volume that is occupied by the vortex.

The lastly named comparator denotes the distance from the entrance to the point where the vortex has reached full development. The filled width is evaluated at a point 20% of the channel distance downstream of the entrance. The filled width and the critical development length are expressed as percentages of the channel width and length, respectively. These comparators are to be given a fuller treatment in the paper to follow,

Subjective comparators of the apparent swirl strength, apparent swirl coherence, and outlet flow development are also used. These comparators assess the perceived ability of the vortex pairs to remain stable and coherent throughout the transition of the simulated fin channel. Lastly, the vortex structure is evaluated for visual evidence of vortex bursting, and the presence of an oval structure in the cross section and the visual presence of the common-downwash region.



a) b) c)

Figure 4. Vortex pairs taken at the downstream end of the test section.

The trials are conducted at 0.5 m/s increments over a range of airflow velocities extending from 0.5 to 10 m/s, thus encompassing that of computers, routers and servers.

VI. Results and Discussion

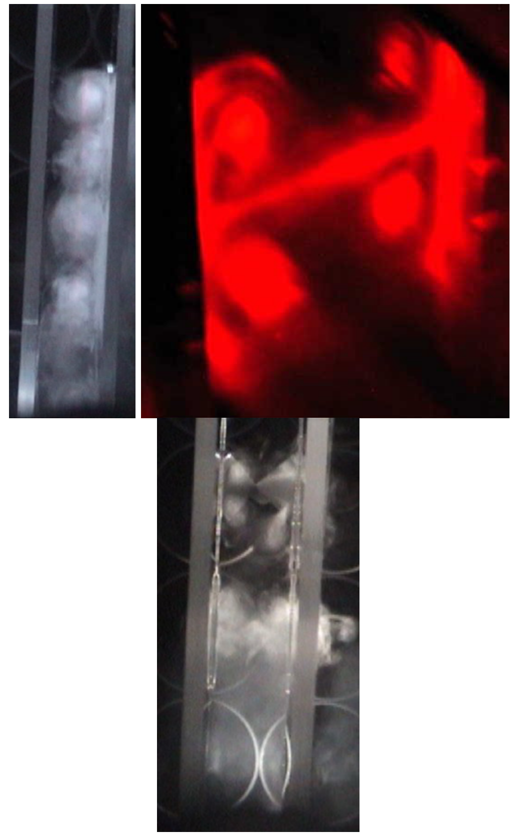
Our experimental results show that within a short distance, the vortices can expand and fill the interfin channel width as well as spread to nearly twice the width in the longitudinal channel height direction. Oval vortex cross sections are observed with the two pairs touching without losing stability and coherence. Figure 4 contrasts three photos taken from a vantage downstream of the test section and looking upstream toward the vortex generator; the latter is mounted on the right side of the test section. The left photo depicts a vortex pair that is circular in shape with a small common-downwash region and weaker recirculation vortices. The structure is clearly visible and the vortices nearly fill the width although not the height of the channel.

The photos of Figs. 4a–b show a pair of oval vortices that nearly fill both width and height to the extent that the corners are also covered. The common-downwash region is clearly visible and dominates the center of the channel. This circulatory motion is very desirable, being favorable to heat transfer augmentation.

The height of the fin channel relative to the width produces a second aspect ratio for the fin channel,

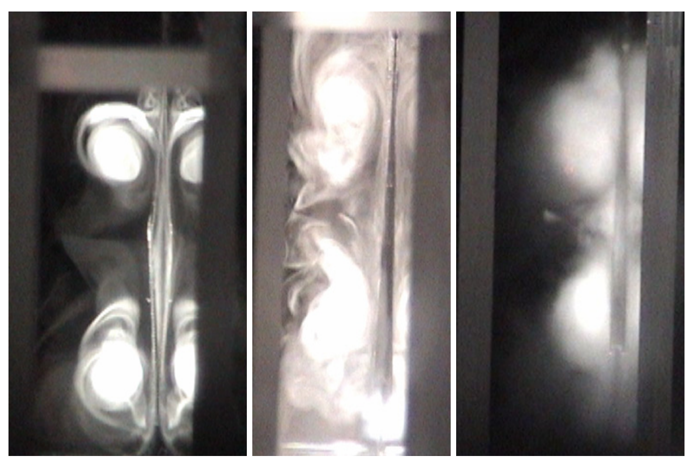
$$\Lambda_{\text{channel}} = \frac{W_{\text{channel}}}{H_{\text{channel}}}$$

In the case where the channel aspect ratio exceeds 4, the vortices will no longer fill the channel height even though the vortices are oval in shape. To overcome this, multiple generators are needed to create a series of vortices. Figure 5 illustrates the creation of multiple vortices within an elongated channel. In Fig. 5a, a pair of stacked vortices is produced by placing two vortex generators on the same side of the channel; in Fig. 5b a pair of vortices are generated by placing a pair of vortex generators opposite each other creating a quadrupole; and in Fig. 5c, four generators are placed two on each side creating stacked quadrupoles. In Fig. 6a, the effect of separating the vortices is due to the wide base of the generator. Finally, Fig. 6b shows the result of using a curved generator while Fig. 6c illustrates the trapezoidal shape's response.



a) b) c)

Figure 5. Multiple vortices within a tall channel.



a) b) c)

Figure 6. Effect of shape on vortex structure.

The influence of the shape on the vortex pair is found to be dependent on the width of the base span, *b*. The wider base span produces a greater distance between the vortex pair's rotational centers. Given an appreciable width, the vortices will separate and leave an open area between the structures. This effect is shown in Figs. 6a–c. The right photo details the structure generated by the trapezoidal shape. This design produces hairpin vortices that are spun off the flat tip and act to constrain the rotational centers. Numerous tests are conducted and cataloged by Dake [44].

VII. Conclusions

Based on a large number of experimental trials, the effect of shape may be summarized as follows:

(1.) The flat shape provides the most stable structure.
(2.) The trapezoidal design induces the most oval shaped vortices with the spacing being a function of the width of the tip.
(3.) The curved shape tends toward smaller, faster rotating vortices with separating rotational centers.
(4.) The double delta design provides the least productive vortices exhibiting small outer diameters and widely spaced centers.

The results of the flow visualization are unmistakable in the conclusion that the angle of attack plays a major role in the development and the percentage of fill of the vortices within the channel. Evaluation of the 72 generators shows that there are distinct differences in performance according to the angle of attack. With but a couple of exceptions, the 60° angle of attack holders have little stability and coherence. The lower angle of attack is clearly more beneficial. Contrary to the trend in the literature toward an angle approximating 45°, the 30° angle of attack produces the widest vortex spread, fill ratios, presence of the common-downwash region, and recirculation zones in each case.

Generator height relative to the channel height is clearly determined to be most effective when the height approaches that of the channel. The diameter of the vortex as determined by the width-to-height ratio indicates that the vortex will rarely exceed a diameter of more than 1.35 times the generator height. For the vortex to fill the channel width, the generator must then reach across 3/4 of the channel width to touch both fins.

Variation of the aspect ratio of the vortex generator proves to be of little consequence. No discernible difference is found with regard to the aspect ratio excepting that the twisting motion of the vortices in the longitudinal direction, parallel to the channel, could be seen in the laser images. The 2.0 aspect ratio appears to give the edge to creating a wider spread in the vortex diameters. Measurement of the pressure drop showed a small effect on the pressure drop in the airstream to be detailed in a later paper.

Using these parameters for design and evaluation, it has been proven that vortices generated by a triangular vortex generator mounted at the entrance to a fin channel may be controlled as to the shape and fill characteristics of the channel. These parameters provide a means to potentially enhance the heat transfer from the heat sink fins to the surrounding air. In a forthcoming study, the favorable flow modulation characteristics will be shown to correlate with enhanced thermal behavior. A detailed discussion of the results are planned for the subsequent papers that will cover the experimental apparatus and data, and the conclusions and application of results. This work will discuss the specific application to heat transfer and the experimental results with temperature data for the various designs.

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