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Printed Circuit Board (PCB) Cooling by Using the Swirl Flow Technology

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Abstract

In this article, the steady-state heat transfer characteristics of PCB in forced convection utilizing the swirl flow through a channel are investigated. A 3-D numerical investigation of forced convection heat transfer for 12 electronic chips in an inline arrangement placed on top of the channel that equipped with a vortex generator is considered. The Nusselt number is explored under two levels of inlet flow angles, namely, 0^o (axial flow without swirl) and 60^o (swirl flow) at Reynolds number, Re, of 1200. The results show that, vortex generator effectively enhances the heat transfer in the channel. The swirl flow demonstrates nearly 22 % enhancement of Nusselt number and nearly 19 % reduction of the surface temperature compared to the axial flow. Such cooling by using the vortex flow eventually fulfill the reduction in thermal stresses and, hence, the desired increase in the system's overall reliability.

Keywords: PCB; Reliability; Vortex Generator; Cooling; Nusselt Number

1. INTRODUCTION

Electronic equipment is used in every aspect of modern life, from dolls and appliances to high-power computers and cell phones. Electronic units are powered by the passage of electric current which causes heat dissipation and temperature rise within the space surrounding them. A high operating temperature lowers the electronic components performance and substantially affects their reliability and safety, where their failure rate is exponentially proportional to the operating temperature. Also, high operating temperatures lead to high thermal stresses in the joints of electronic components attached on circuit boards which lead to their failure. Hence, the need for thermal control has become significantly vital in the design and operation of electronic devices.

Many attempts were made by researchers to essentially enhance the reliability and, hence, the overall performance of the printed circuit boards. A comprehensive review of convection cooling of electronics packages is provided by Incropera [1], Peterson and Ortega [2] and Sathe and Sammakia [3]. Manglik and Bergles [4] showed that the swirl flow may augments the convective heat transfer. Ali [5] applied rectangular vortex generator to an experimental setup to study its effect on thermal performance electronic component near a wake region, a 14.5 % increase in heat transfer was reported when applying vortex generator.

Aneesh et al. [6] studied various printed circuit heat exchanger models with wavy channel, including: trapezoidal, sinusoidal and triangular configurations as well as straight channels. The trapezoidal model was found to have the highest heat transfer with the largest pressure drop. Convective heat transfer characteristics for laminar air-flows over a ribs horizontally-oriented simulated PCB assembly have been measured and predicted by Leung et al. [7], they found that Nusselt number depends on the rip aspect ratio. Liou et al. [8] used transient liquid crystal thermography technique to measure the local Nusselt number in a channel that equipped with twelve different vortex generator. Delta Configuration significantly increased the Heat transfer by 170% with 30% increase in friction factor. Luan et al. [9] compared the flow structures and thermal performance in a swirl chamber. Results showed that the highest performance was achieved in the converging inlet swirl chamber. The intensity of heat transfer is substantially improved with the increase of Reynolds number. Haque and Betz [10] carried out numerical investigation of forced convection heat transfer over an in-line arranged electronic blocks equipped with elliptical shaped vortex generators. The block is prescribed with a 1000 W/m^2 heat flux due to heating of the electronic components installed in the CPU casing. The results showed that, vortex generators could effectively enhance the heat transfer in the channel.

Experimental investigation was carried out by Leung and Kang [11] with printed board assembly slanting in both horizontal and vertical positions. The heat transfer measurements were obtained for moderate Reynolds number ranging from 510 to 2050. Lohan et al. [12] measured the surface temperature distribution of five different types of PCBs using infra-red thermography technique, results were compared to the numerical predictions from CFD code. The jet provided momentum transfer and enhances interaction with the surface leading to formation of vortices that enables efficient heat transfer is studied by Black et al. [13]. Inside the enclosure, Nusselt number for both hot and cold walls was reported by Ha and Jung[14]. Wang et al. [15] simulated an obstruction block movement above a heated chip and they showed that the induced trajectories of the obstruction block motion have substantial effects on the chip cooling. DNS and LES simulations were carried out by Sohankar [16] for unsteady heat transfer analysis in a channel with V-shaped vortex generators. The vortex generators were attached at the bottom of the channel with angle of attack that varies between 10° and 30°. Friction factor and Colburn factor were calculated. They reported that heat transfer rate was greatly improved with the implementation of the vortex generators.

Davalath and Bayazitoglu [17] numerically examined the forced convection between two dimensional parallel plates equipped with three uniformly heated rectangular blocks. The extended surfaces increased both heat transfer area as well as the mixing levels and as a result, the heat transfer rate was substantially improved. Local Nusselt number correlation for both insulated and uninsulated plates were presented for different values of Reynold's number.

This paper is devoted to discuss the effects of swirl-forced convection technique for cooling the printed circuit boards (PCBs) in order to increase the system's overall reliability. The effect of vortex flow inside a channel that equipped with electronics chips will be investigated for enhancement of the heat transfer in term of Nusselt number. Numerical techniques CFD code developed by Fluent 6.3 will be implemented. The Nusselt number and the surface temperature will be explored under two levels of inlet flow angles, namely, 0^o (axial flow without swirl) and 60^o (swirl flow) at Reynolds number, Re, of 1200.

2. NUMERICAL METHOD

The PCBs assembly considered in this study is assumed to be operating under three-dimensional, laminar, incompressible, and steady flow conditions. Fluent 6.3 is implemented as an advanced computational technology that enables us to understand the augmented heat for PCBs, and subsequently improve its reliability.

2.1. Geometry and Materials

A printed circuit board (300 mm x 100 mm) is equipped with 12 electronic chips [(30 x 15 x 3 mm/chip) with a total heat generation of 24 W (2 W/chip)] that are not allowed to come into direct contact with air for reliability reasons. The electronic unit need to be cooled by passing cool air through a 300 mm long channel of rectangular cross section 100 x 40 mm drilled into the board (see Fig. 1(a)). The heat generated by the chips is transferred across the layers of the board to the cooling channel, where it is convected by flowing air that enters the channel at 295 K. The heat flux at the top surface of the channel can be considered to be uniform, and heat transfer through other surfaces is negligible. A vortex generator that generate vortices inside the PCB channel is connected to the channel as shown in fig. 1(b). The PCB channel dimensions are given in Table 1.

The vortex generator has a cylindrical structure with diameter, D, of 30 mm, and length, f, of 40 mm. The vortex generator has four inlets holes where the air is induced and a number of holes with a diameter, d, of 14 mm are drilled at two specified angle of ϕ = 0^o (axial flow without swirl) and ϕ = 60^o (swirl flow). When the air flows via an inclined holes (namely ϕ = 60^o) through the vortex generators, it is directed to enter the channel in the tangential path so that swirl is created inside the PCB assembly. Meanwhile, when the air flows via an angle ϕ = 0^o, the flow enters the generator radially then directed axially through the channel.

The simulations were performed at inlet velocity, V_{in}, of the air at vortex generator inlets holes is 2 m/s at mass flow rate, $\dot{m}$, of 0.0015 kg/s, which correspond to Reynolds number, Re, of 1200, where Reynolds number is defined as

$$R_e = \frac{D_h \dot{m}}{A \ \mu} \tag{1}$$

where D_h is the hydraulic diameter of the channel and A is the cross sectional area of the channel.

In addition, the simulations were performed at two levels of inlet flow angles, namely, 0^o (axial flow without swirl) and 60^o (swirl flow).

The air density, ρ , of 1.225 kg/m^3, the specific heat, c_p, of 1.006 kJ/kg.k, thermal conductivity, k, of 0.0242 w/m.k, prandtl number, p_r, of 0.71 and viscosity,μ , of 1.79 x 10 $^{-5}$ kg/m.s are assumed for this present simulations.

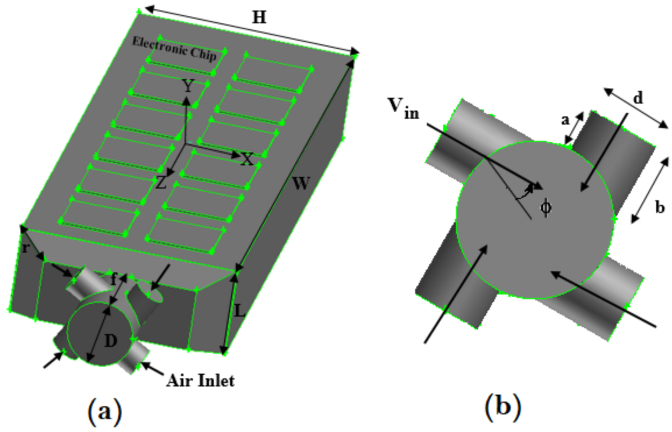

Fig. 1. Schematic of the geometry of the printed circuit board assembly used in this study **(a).** The printed circuit board channel equipped with 12 electronic chips (30 x 15 x 3 mm/chip) with a total heat generation of 24 W (2 W/chip) **(b).** Vortex generator that shows the generation of vortices inside the PCB channel.

Table 1: Dimensions of the printed circuit board assembly.

W	H	L	D	F	d	ϕ	r	a	b
300 mm	100 mm	40 mm	30 mm	40 mm	14 mm	0^0 & 60	30 mm	12 mm	20 mm

2.2. Boundary Conditions and Numerical Schemes

Uniform velocity and temperature are assigned normal to the inlet faces of the openings of the vortex generator (V_{in}.= 2 m/s, Tin =295 k). Pressure-outlet condition is assumed at the channel exit boundary. At the walls, the no-slip condition was adapted. The heat flux at the top surface of the channel can be considered to be uniform (12 W), and heat transfer through other surfaces is negligible. The SIMPLE algorithm was used for pressure-velocity coupling. Regarding the discretization schemes, SIMPLE scheme is used for pressure, whereas second order upwind is used for both energy and momentum. Practice has shown that usually 12000 iterations necessary for data convergence and stabilization.

The numerical simulations were performed on a 3-D unstructured grid. Tetrahedral/Hybrid mesh scheme – TGrid was used. A grid- independent solution study was done by execution the calculations at three different grids sizes comprising of 400587, 704672, and 905873 nodes. It turned out that the maximum difference between the results of the coarsest and finest grids in term of Nusselt number and temperature fields was less than 4%, suggesting that the grid-independent results could be achieved with a coarser mesh of 400587 nodes.

However, to eliminate any uncertainty and to resolve the predictable large parameter gradients, simulations were performed by meshing the channel with 704672 nodes.

3. RESULTS AND DISCUSSION

In order to make sure that the modeling approach is effective in simulating PCBs assembly, the common analytical solution for axial flow is adopted as a benchmark to validate the current modeling approach. In the case of constant heat flux, the mean fluid temperature at the channel exit can be expressed as

$$T_e = T_i + \frac{\dot{q} A_s}{\dot{m}\, c_p} \qquad (2)$$

Where T_e is the exit temperature, T_i is the inlet temperature, $\dot{q}$ is the heat flux, and A_s is the surface area. The surface temperature for constant heat flux can be written as

$$T_s = T_m + \frac{\dot{q}}{h} \qquad (3)$$

Where T_s is the surface temperature, T_m is the mean air temperature, and h is convection heat transfer coefficient. The Nusselt number N_u is given by

$$N_u = \frac{h\, D_h}{k} \qquad (4)$$

Where D_h is the hydraulic diameter of the channel which is equal to 57 mm. The average Nusselt number for developing laminar flow can be determined from the correlation equation that developed by Sieder and Tate [18]

$$N_u = 1.86\left(\frac{R_e\, P_r\, D_h}{H}\right)^{1/3} \qquad (5)$$

The present simulation captured the behavior of the surface temperature and the surface Nusselt number for the PCB as shown in Fig. 2 and Fig. 3. The contour of static temperature at the upper surface for an inlet angle of $\phi = 0^0$ (axial flow without swirl) is depicted in Fig.2a, while the contour of static temperature at the upper surface for an inlet angle of $\phi = 60^0$ (swirl flow) is depicted in Fig.2b. These figures clearly illustrate that the surface temperature increases with the flow direction for both cases but its higher in axial flow than in swirl flow. The maximum surface temperature at the exit reaches 224°C for axial flow while 174°C for swirl flow. The surface temperature of the channel remains under 174°C means the maximum total power of the electronic components that can safely be mounted on this circuit board can be achieved with swirl flow rather than the axial flow. To get confidence from this result, equations (2-5) are used to get the maximum surface temperature for axial flow ($\phi = 0^0$). The comparison between the current simulation and the analytical solution agrees well. It is also noted from figure 2 that the surface temperature is not evenly distributed due to swirl motion mechanism.

The contour of Surface Nusselt at the upper surface for an inlet angle of $\phi = 0^0$ (axial flow without swirl) is depicted in Fig.3a, while the contour of Surface Nusselt at the upper surface for an inlet angle of $\phi = 60^0$ (swirl flow) is depicted in Fig.3b. In both cases, the swirl number drops with flow direction, but the average Nusselt number in case of swirl flow ($\phi = 60^0$) is higher than the axial flow ($\phi = 0^0$).

The dimensionless temperature, Ψ, is defined according to the following equation.

$$\Psi = \frac{T_s - T_i}{T_o - T_i} \qquad (6)$$

The dimensionless temperature, Ψ, is shown in Fig. 4 for both cases of $\phi = 0^0$ (axial flow) and $\phi = 60^0$ (swirl flow). In both cases the dimensionless temperature increases in the flow direction, however, its value in the swirl flow less than that in the axial flow. This is a vital sign that indicate and ensure safe and reliability using of swirl flow for cooling the PCB. The fluctuating of temperature that appears in Fig. 4 is due to the location of electronic chips on the surface. The swirl flow demonstrates nearly 19 % reduction of the dimensionless temperature compared to the axial flow.

The Nusselt number distribution is shown in Fig. 5 for $\phi = 0^0$ (axial flow) and $\phi = 60^0$ (swirl flow). It decreases with flow direction for both cases but it is the highest for swirl flow. In case of swirl flow, the Nusselt number decreases with the flow direction due to fact that the swirl velocity decays from the vortex generator toward the PCB channel, which can be attributed to damping effects. The swirl flow augments the convective heat transfer coefficient and hence increases the Nusselt number comparable to the axial flow. The simulated average Nusselt number has been compared to work of Sieder and Tate [18] as depicted in Fig. 5. For axial flow, the average Nusselt number is 11 and agrees with present simulation. Vortex generator tends to increase the secondary flows and consequently enhance mixing to form coherent fluid motions in the form of stream wise-oriented vortices. Such vortices increase the advection of heat away from surfaces and hence increase the convective heat transfer coefficient. The swirl flow demonstrates nearly 22 % enhancement of Nusselt number compared to the axial flow.

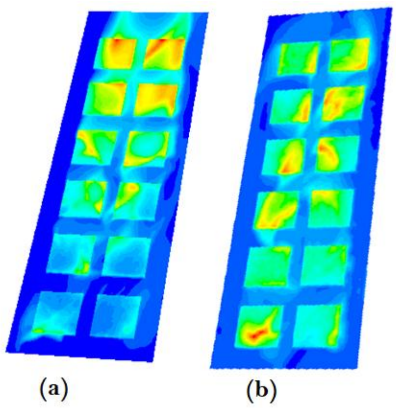

Fig. 2: Contour of static temperature at the upper surface: (a) $\phi = 0^0$, (b) $\phi = 60^0$

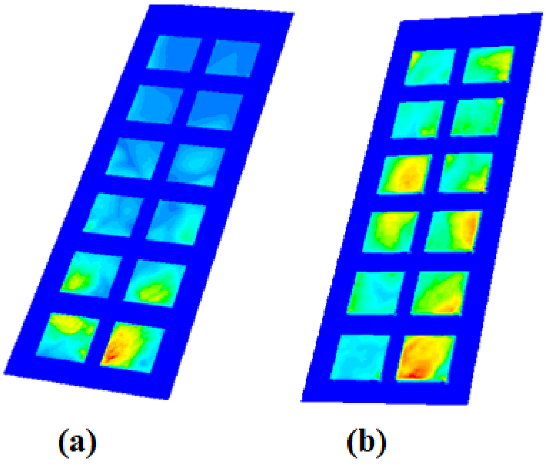

Fig. 3: Contour of Surface Nusselt Number:
(a) $\phi = 0^0$, (b) $\phi = 60^0$

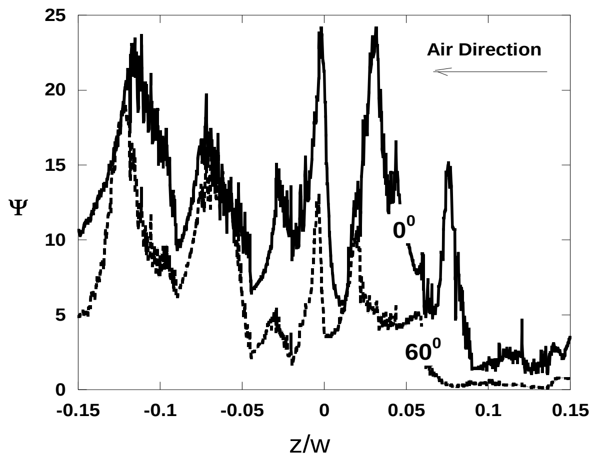

Fig.4 : Dimensionless temperature at the upper surface for $\phi = 0^0$ and $\phi = 60^0$

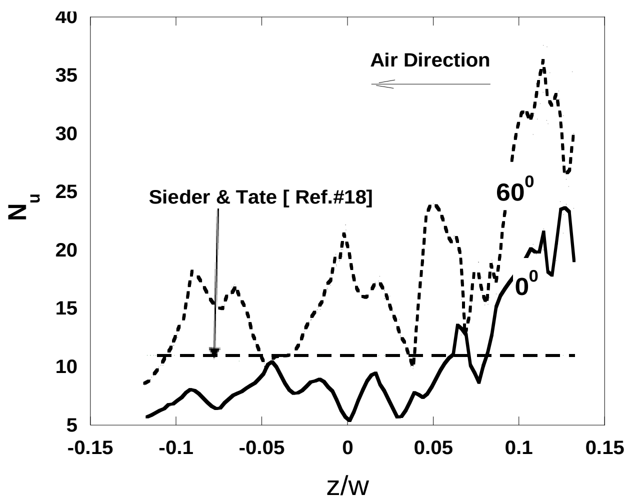

Fig.5: Nusselt number (Nu) at the upper surface for $\phi = 0^0$ and $\phi = 60^0$

4. CONCLUSION

The current paper is devoted to particularly discuss the effects of swirl-forced convection technique numerically on the cooling of printed circuit boards (PCBs). A 3-D of the printed circuit board channel equipped with 12 electronic chips (30 x 15 x 3 mm/chip) with a total heat generation of 24 W (2 W/chip) equipped with the vortex generator has been deliberated. The Nusselt number and the surface temperature are explored under two levels of inlet flow angles, namely, 0° (axial flow without swirl) and 60° (swirl flow) at Reynolds number, Re, of 1200. It is found that the vortex generator significantly increases the convective heat transfer coefficient and hence increases the Nusselt number. In addition, there is much reduction in surface temperature which is virtuous indication for safety issues.

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