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# Thermo-fluid analysis of micro pin-fin array cooling configurations for high heat fluxes with a hot spot

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ABSTRACT

Effect of micro pin-fin shapes on cooling of high heat flux electronic chips with a single hot spot was investigated numerically. Hydrothermal performances of different micro pin-fin shapes were evaluated. Circular shape, hydrofoil shape, modified hydrofoil shape, and symmetric convex shape were the cross section shapes used for micro pin-fins. All cooling configurations had the same staggered arrangements for micro pin-fins. An electronic chip with a 2.45 × 2.45 mm footprint having a hot spot of 0.5 × 0.5 mm at its centre was used for simulations. Uniform heat flux of 2000 W cm$^{-2}$ was applied at the hot spot. The rest of the chip was exposed to 1000 W cm$^{-2}$ uniform heat load. The cross section area of the circular shape and hydrofoil shape micro pin-fins was kept the same to have a fair comparison. Convex and hydrofoil shape designs showed significant reduction in the required pumping power as well as the maximum required pressure. In the last case, the height of micro pin-fins was increased from 200 μm to 400 μm to remove 100% of the total heat load *via* convection, and at the same time keep the maximum temperatures within an acceptable range.



## 1. Introduction

Three-dimensional (3-D) integrated circuits (ICs) are believed to be the best way to overcome barriers in inter-connect scaling and keep Moore's law ticking by providing an opportunity for continued higher performance ICs in the semiconductor industry [1]. Smaller size, higher performance, better functionality and lower consumption of power are some of the major advantages of 3-D ICs. On the other hand, increasing demand for removing heat from 3-D ICs has become the major challenge in this field and has constrained their applications. The next generation of the electronic chips is expected to produce heat fluxes up to 500 W cm$^{-2}$ as the background and more than 1000 W cm$^{-2}$ at hot spots [2,3].

Sahu et al. [4] applied a hybrid cooling scheme which combines microfluidic and solid-state cooling techniques in cooling hot spots with the heat flux close to 250 W cm$^{-2}$. In other research, Sahu et al. [5] studied a liquid-thermoelectric hybrid cooling method for hot spots having heat fluxes of more than 600 W cm$^{-2}$. They reported that liquid-thermoelectric hybrid cooling showed better results for higher heat fluxes at hot spots. Abdoli and Dulikravich [6] performed multiobjective optimization for multi-layer straight and branching counterflow microchannel configurations with 67 design variables to maximize heat removal capacity, while minimizing temperature non-uniformity and coolant pumping pressure drop. They also optimized the multi-layer through-flow microchannels for heat fluxes up to 1000 W cm$^{-2}$ [7]. Abdoli et al. [8] also performed a fully 3-D thermal-fluid-stress-deformation analysis for cooling chips with 1000 W cm$^{-2}$ background heat flux and up to 2000 W cm$^{-2}$ heat flux at the hot spot. They reported that multi-floor microchannels are capable of cooling such chips without exceeding the maximum allowable stresses.

Micro pin-fins have shown very promising results in conveying heat from multiple layers to the heat sink [9,10]. Alfieri et al. [11] numerically investigated cooling of 3-D stacked chips with 50 W cm$^{-2}$ background and 125 W cm$^{-2}$ hot spot heat fluxes. They studied the influence and implications of the integrated water cooling, micro pin-fins distribution and sizes also influence temperature of hot spots. Alfieri et al. [12] in another research modelled vortex shedding in water cooling of 3-D integrated electronics. Zhang et al. [13,14] experimentally investigated effects of silicon micro pin-fin heat sink with integrated TSVs in cooling high power chips. Dembla et al. [15] also studied the fine pitch TSV integration in silicon micro pin-fin heat sinks for 3D ICs with 100 W cm$^{-2}$ heat load.

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In the present work, fully 3-D conjugate thermo-fluid analysis of micro pin-fins was performed for four geometrically different cross sections micro pin-fins: a conventional circular shape, a hydrofoil shape, a modified hydrofoil shape and a symmetric convex lens shape. In Sections 2–5, results of these four different designs with the same boundary conditions are presented. Section 6 shows the results of symmetric convex lens micro pin-fins with adiabatic bottom surface. In the last cooling case, height of the micro pin-fins was doubled to reduce the maximum temperature at the top and bottom surfaces.

## 2. Case 1: micro pin-fins with circular cross section

An array of cylindrical shape micro pin-fins was virtually designed for cooling an electronic chip with dimensions of $2.45 \times 2.45 \times 0.28$ mm. Fig. 1 shows the staggered arrangement of the micro pin-fins and the spacing between them. A hot spot with dimensions of $0.5 \times 0.5$ mm was located at the centre of the chip. A total of eleven crossflow rows of micro pin-fins can be observed in Fig. 1. Six of these rows included nine micro pin-fins and five of them included eight micro pin-fins. The reason for staggered arrangement of micro pin-fins was to enhance the convection heat transfer [16]. Fig. 1b shows that centre-to-centre distance between micro pin-fins was 250 μm. The side walls thickness was 60 μm. The bottom and top walls were 40 μm thick. Diameter of each micro pin-fin was 173 μm. Most of the geometric arrangements and sizes were adopted from Refs. [13–15]. Material for substrate and micro pin-fins was assumed to be Silicon and coolant was water.

All 3D conjugate heat transfer simulations presented in this paper were carried out using ANSYS Fluent® software [17]. ANSYS meshing® was adopted as the computational grid generation tool. Considering the geometry and physics of the problem, all cases were eligible for symmetric assumption. Therefore, all geometries were cut in half in the streamwise direction to reduce computational costs noticeably. Standard k–ε turbulent model was used in all cases due to its stability, good convergence rate and relatively low required memory. A hybrid mesh with viscous sub-layer refinement next to solid surfaces was used for discretization of the solution domain. The viscous sub-layer mesh had the minimum height of 1 μm with growth rate of 1.2. Mesh independency was reached for a mesh with 6,900,000 cells. A sample of the hybrid mesh is presented in Section 4 which has sharper edges.

Inlet averaged speed and temperature of water were set to 2.0 m $s^{-1}$ and 26.85 °C, respectively. The outlet gauge pressure was set to 20 kPa. The temperature gradient normal to the outlet was set to zero. Coolant boundary conditions were kept the same for all cases. The following are the applied boundary conditions for the solid domain:

**Table 1**
Case 1 – micro pin-fins with circular cross section: geometric parameters.

| Design parameter | Value | Design parameter | Value |
|---|---|---|---|
| Number of micro pin-fins | 94 | Total wetted area of micro pin-fins ($mm^2$) | 10.23 |
| Total cross section area of all micro pin-fins ($mm^2$) | 2.215 | Micro pin-fin area ratio (wetted area/cross section area) | 4.62 |

1. Constant input heat flux of 2000 W $cm^{-2}$ for the hot spot on the top surface,
2. Constant input heat flux of 1000 W $cm^{-2}$ for background on the top surface,
3. Constant temperature of 26.85 °C on the bottom surface,
4. Thermally insulated side walls.

The bottom surface temperature was assumed to be close to the room temperature as in an ideal situation. These thermal boundary conditions were also kept the same for the next three cases. In the last two cooling cases, the thermally insulated boundary condition was enforced at the bottom surface as in a worst-case scenario.

Some of geometric parameters of micro pin-fins with circular cross section are given in Table 1. Total number of micro pin-fins was 94. The ratio of the total wetted area (fluid contact area) of this arrangement of micro pin-fins to the total cross sections area (chip contact area with one micro pin-fin) in this case was 4.62.

Fig. 2 shows thermo-fluid analysis results for this case. Temperature distribution in the entire half of the configuration is shown in Fig. 2a. The coolant flow direction was in the x-direction. The maximum temperature in this case was 78.95 °C which occurred at the hot spot. Higher temperature region can also be observed near the coolant outlet. Fig. 2b illustrates the temperature variations in micro pin-fins in one half of the configuration. Micro pin-fins under the hot spot had the maximum temperature. Also, higher temperatures can be seen near the flow exit. Fig. 2c shows the heat flux distribution normal to the bottom surface. This is an indication of the heat removed from the chip by conduction. As this figure illustrates, conduction heat transferred portion was increased in the streamwise direction. This is due to water temperature increase in this direction, which resulted in a decrease in convection heat transfer and an increase in conduction heat transfer. The maximum conduction occurred under the hot spot. This shows that the convection heat transfer *via* water was not

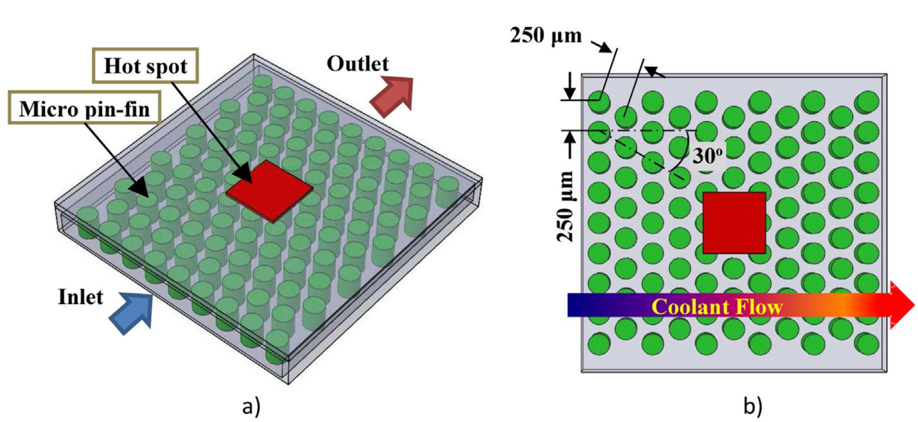


**Fig. 1.** Case 1 – cylindrical micro pin-fins with circular cross section: a) 3-D view, and b) top view with dimensions.