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A numerical investigation of thermal airflows over strip fin heat sinks☆

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ABSTRACT

The benefits of using strip fin heat sinks (SFHSs) where the cross-sectional aspect ratio of the fins lie between those for plate fins (high aspect ratio) and pin fins (aspect ratio ≈ 1) are explored computationally, using a conjugate heat transfer model. Results show that strip fins provide another effective means of enhancing heat transfer, especially when staggered arrangements of strip fins are used. A detailed parameter investigation demonstrates that perforating the strip fins provides additional improvements in terms of enhanced heat transfer, together with reduced pressure loss and heat sink mass. Results are also given which show that, for practical applications in micro-electronics cooling, perforated SFHSs offer important benefits as a means of achieving smaller processor temperatures for reduced mechanical power consumption.

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1. Introduction

The inexorable rise in heat flux densities from micro-electronic components and devices is presenting the industry with formidable challenges in maintaining processor temperatures below critical values, in order to circumvent a range of important failure modes, [1]. These challenges have stimulated a number of cooling innovations, including the use of highly conductive inserts to provide more efficient pathways to heat removal, [2], and a number of promising liquid cooling methods. The latter include on-chip cooling, direct liquid jet impingement and dielectric liquid immersion which removes heat by convection currents, [3].

This paper focuses on what remains currently the most popular approach for cooling microelectronics, namely convective heat transfer to air as it flows over a network of extended surface fins on a heat sink. It has recently been estimated that heat sinks account for more than 80% of the thermal management solutions for electronics, which will be worth over $10 billion in 2016 [4]. Heat sinks provide a low cost and reliable means of achieving a large total heat transfer surface area without excessive primary surface area, and the surface fins act as turbulence promoters which enhance heat transfer rates by breaking up the thermal boundary layer. The main goals of heat sink design are to provide sufficient heat transfer rates, to ensure that processor temperatures remain below critical values, for minimal pressure loss and heat sink mass, see e.g. [5].

Heat sinks based on rectangular plate fins (PFHSs) are the most common. Several experimental and numerical studies of PFHSs have appeared in the literature, see e.g. [6,7], and these have demonstrated that the heat transfer rate can be improved by modifying the arrangement of the fins by, for example, employing staggered arrangements of plate fins, see e.g. [8,9], or periodically interrupted diverging and converging fins, [10]. Generally, it is found that staggered arrangements of plate fins can improve heat transfer but at the cost of significantly larger pressure drops across the PFHSs.

A number of recent studies have shown that perforating the fins in PFHSs can lead to localised air jets which result in substantial improvements in heat transfer rate with reduced pressure losses. Shaeri and Yaghoubi [11] and Dhanawade and Dhanawade [12] studied thermal air flows through arrays of plate fins, with one or more rectangular perforations respectively parallel to the dominant flow direction. They found that perforations reduce the pressure loss by reducing the size of the wakes behind the fins and the length of the recirculation zone around the lateral surface of the fins, whereas air jets through the perforations generally enhance the heat transfer rate. Ismail et al. [13] also found that the shape of the perforations can be influential and that the pressure drop with circular perforations is substantially smaller than with square ones.

The plate fins on heat sinks are often replaced by pins with a much smaller cross-sectional aspect ratio, typically with the ratio of fin length to width AR ≈ 1, see Fig. 1. These are often referred to as pinned heat sinks (PHSs) and several studies have shown that PHSs can be much more effective at disrupting the boundary layer and improving rates of heat transfer, see e.g. [14,15], but at the cost of much larger pressure drops. The effect of pin arrangement in terms of pin density and orientation to the dominant flow direction (either in-line or staggered) has also been shown to be very influential in PHSs. Generally, increasing pin density and employing staggered arrangements of pins both lead to increased rates of heat transfer and larger pressure losses, [8,16–19].

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Nomenclature

A_c	cross-sectional area of the flow passage of the heat sink, m^2
D	pin diameter of the pin fin heat sink, mm
d	perforation diameter of the pin fin, mm
D_h	hydraulic diameter, m
H	pin fin height, mm
θ	thermal resistance, K/W
h_p	projected heat transfer coefficient, W/m^2·K
h	heat transfer coefficient, W/m^2·K
k	turbulence kinetic energy, kg m^2/s^2
n	number of perforations
N	number of pins
L	heat sink length, mm
Nu	Nusselt number
P	fan power, W
Δp	pressure drop, Pa
Pr	Prandtl number
Pr_t	turbulent Prandtl number
Q	power applied on the base, W
S_z	pin pitch in streamwise direction, mm
Re	Reynolds number
T	temperature, °C
ΔT	temperature difference, °C
U	air velocity, m/s
θ_s	thermal resistance in terms of surface area, K m^2/W
T_{base}	base temperature, °C
h_T	Total heat transfer coefficient, W/m^2·K
Greek	
α	fluid thermal diffusivity (m^2/s)
α,β,β^*	turbulence model constants
ϕ	porosity V_{void}/V
μ	fluid viscosity (Pa·s)
μ_t	turbulent eddy viscosity, Pa·s
ρ	fluid density (kg/m^3)
ν	kinematic viscosity, m^2/s
ν_t	turbulent kinematic viscosity, m^2/s
σ_ε	k-ε turbulence model constant
σ	turbulence model constant for the k-equation
ω	k-ω turbulence model constant

In comparison with PFHSs, relatively few studies have considered the effect of perforations on heat transfer and pressure drops in PHSs. Sahin and Demir [20,21], for example, studied the effect of cross-sectional shape (circular or square) for in-line pin arrays while Dhumne and Farkade [9] considered the effect of staggered pin arrangements for singly-perforated pins of circular cross-section. Dai et al. [22] studied the benefits of micro-jets to improve heat transfer rate and reduce pressure drop by inducing flow separation in PHSs. Collectively, these studies have shown that perforations can also lead to substantial improvements in heat transfer for reduced pressure losses for PHSs. Al-Damook et al. [15] have very recently used complementary experimental and numerical methods to explore the benefits of using multiple pin perforations within PHSs. They showed that the heat transfer rate increases monotonically with the number of pin perforations, while the pressure drop and fan power, required to overcome the pressure drop, both reduce monotonically; the location of the perforations was found to be much less influential. Their conjugate heat transfer analysis showed, further, that improved heat transfer with pin perforations leads to significantly reduced processor case temperatures and pin mass. Their experiments also revealed that practical considerations, including pin perforation alignment with the dominant flow direction and the quality of the pins' surface finish, can affect the heat transfer and pressure drop significantly.

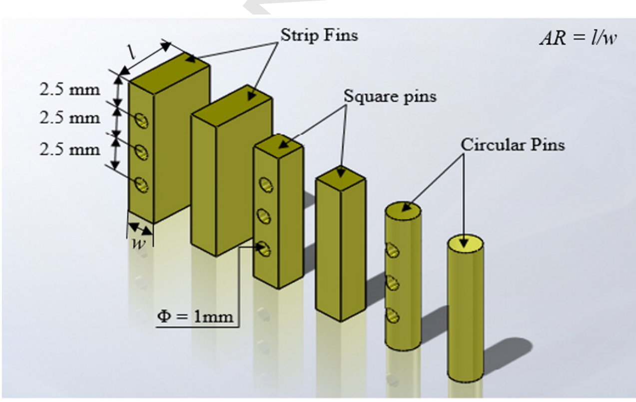

Fig. 1. The six fin designs considered, and a definition of pin aspect ratio, AR = l/w.

Most studies of PHSs to date have considered cases where the pins have cross-sectional aspect ratios, AR ≈ 1. The present study focuses on the benefits of employing pins with a larger aspect ratio, AR = 2.25, as a compromise between the simplicity of PFHSs and the need to employ several small pins on PHSs. Such heat sinks are referred to here as strip fin heat sinks (SFHSs) and very few previous studies of SFHSs have appeared in the literature. Jonsson and Moshfegh [23], for example, studied the performance of strip fins, square pins, circular pins, and plate fins with in-line and staggered arrangements. Using a coarse arrangement of strip fins with AR = 5.3, the pressure drop in their experiments was substantially lower than for a denser arrangement of pins but with a similar thermal resistance. Hong and Cheng [24] studied the performance of strip fins in staggered arrangements in a micro-channel heat sink. They varied the fins' length and the spaces between fins to find the optimal design. Their results showed that SFHSs clearly enhance the rate of heat transfer and that the pressure drop is strongly related to strip fin spacing.

The present study is the first detailed numerical investigation into the benefits of employing perforations in SFHSs. It compares the thermal and hydraulic performance of staggered and in-line arrangements of strip fins with PHSs with circular and square pins of AR = 1, and shows how these can be further enhanced by perforating the strip fins. The paper is organised as follows. Section 2 describes the conjugate heat transfer model for the heat sink problems under consideration and the numerical methods used to solve them. A comprehensive set of solutions is presented in Section 3 and conclusions are drawn in Section 4.

2. Numerical methods

2.1. Problem description

The heat sink designs considered are shown in Fig. 1 with circular and square pins, of cross-sectional aspect ratio AR = l/w = 1, and strip fins with AR = 2.25, where l, and w are the fin length and width respectively. Those values are chosen to facilitate a convenient comparison with the PHSs considered here. Heat sinks with solid and perforated fins in in-line or staggered arrangements shown in Fig. 2 are investigated. The perforated fins contain three circular perforations aligned with the direction of flow and the diameter of each perforation is 1 mm. The case with circular pins in an in-line arrangement has recently been studied by Al-Damook et al. [15]. The dimensions of the base plate, fin height and fin thickness or diameter are the same for all heat sinks and are equal to 50 × 50 mm, 10 mm and 2 mm, respectively. The number of fins is 64 for those with in-line arrangement and 60 for heat sinks with a staggered configuration. Following Al-Damook et al. [15], the heat sinks are aluminium with thermal conductivity 202 W/m·K and with a base plate thickness of 2 mm.

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