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General correlations among geometry, orientation and thermal performance of natural convective micro-finned heat sinks

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ABSTRACT

The interest in micro-technologies has increased in the last decades, because of the low volumes and high performance granted by their application. Micro-fins can find application in several fields, such as power electronics, concentrating photovoltaics and LED. Although micro-technologies have been widely applied in cooling, there is still a lack of knowledge on the thermal behavior of micro-finned heat sinks under natural convective conditions. In the present study, the correspondences between fin geometries and heat transfer coefficients, as well as the effects of the orientation, are experimentally investigated using silicon micro-finned heat sinks with different geometries. The heat sinks are made of 5 cm × 5 cm squared silicon wafer and the fin height ranges between 0.6 mm and 0.8 mm, the spacing between 0.2 mm and 0.8 mm and the thickness between 0.2 and 0.8 mm. Power loads higher than those considered in previous works are studied. The experimental setup is validated using a software simulation and the Nusselt number correlation available in literature. The influence of the fin thickness on this parameter is analyzed and a modified correlation is proposed. Also, the effect of the radiative heat exchange on the overall heat transfer is considered and commented. An analysis of the uncertainty is conducted and reported too.

1. Introduction

Cooling, intended as removal of waste heat, is one of the major issues in many electronic applications, industrial processes, and power generation systems. Cooling technologies are usually classified in active or passive. An active system requires mechanical or electrical power in input. A passive cooling system does not require any power in input, because it just exploits the natural laws: these technologies are usually much simpler and less expensive that the active ones.

Among the passive cooling systems, fins represent one of the most common solutions. The enhancement in heat transfer is essentially achieved by increasing of exchanging surface. Macro-fin arrays have been widely investigated and are a proved and well-known solution, extensively used in many circumstances. Nagarani and his team [1] grouped the researches on fins into two categories: (a) the determination of the profile of the fin for a given quantity of heat transfer rate, and (b) the determination of the fin dimensions for a given fin form and a desired cooling rate. Bar-Cohen and his colleagues [2,3] presented a methodology to optimize the design of finned heat sink in natural convection. Dayan et al. [4] first investigated the behavior of downward facing macro-finned heat sinks in natural convection. In 2012, Do et al. [5] reported the results of their research on a tilted natural convective, plate-finned heat sink, showing the effects of the inclinational angle on the thermal exchange at macro scale. Recently, Tari and Mehrtash [6,7] have further investigated the performance of tilted finned heat sink.

In a world that is moving in the direction of micro-scaled electronic products, the interest around micro-cooling technologies, such as micro-fins, is quickly increasing: they assure faster performance, requiring both less space and less material than the macro-scale coolers. Micro cooling technologies have been already extensively researched, for electronic cooling purposes mainly [8]. This interest has rapidly grown in the last two decades [9] and has been driven by the necessity of more-efficient coolers to manage the heat waste produced by miniaturized electronic components [8]. Passive micro-finned heat sinks can be applied in many circumstances, such as electronics [10], solar power generation [11] and LED applications [12]. These technologies generate high rate of waste heat that needs to be quickly, cost-effectively and high-efficiently removed, but further investigations are still required. So far, active cooling technologies have been mainly employed [13], but the use of micro-fins in a natural convective cooling has

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Nomenclature

A	surface
F	view factor
g	gravitational acceleration
H	fin height
h	heat transfer coefficient
h_{tot}	average heat transfer coefficient
I_{DC}	current supplied in input
k_{air}	thermal conductivity of air
L	length of the array
N_{fins}	number of fins
Q	heat power
Q_{in}	power in input
Q_r	radiative heat through the fins
r	hydraulic radius
s	fin spacing
t	fin thickness
T_{amb}	ambient temperature
t_b	base thickness
T_{back}	temperature of the back surface of the case
v	kinematic viscosity of the air
V_{DC}	voltage supplied in input
W	width of the array
x	geometric parameter
x_{μ}	micro-fin global shape parameter
y	geometric parameter

Dimensionless numbers

Nu	Nusselt number
Pr	Prandtl number
Ra	Rayleigh number (based on characteristic length)
Ra_r	Rayleigh number (based on hydraulic radius)

Greek symbols

α	Thermal diffusivity of air
β	Volumetric thermal expansion
ε	Emissivity
σ	Stephan-Boltzmann constant

Subscripts

fins	Refers to the finned array
flat	Refers to the flat sample
i	Refers to the *i*-wall of the fin
loss	Refers to the losses happening on the case
tot	Refers to the combined radiative and convective exchange

Prefixes

U	Uncertainty

the potential to grant benefits both in terms of heat dissipation and cost saving [14].

Micro-fins can address the requirements for smaller volumes and lower costs that are currently sought after by industries and customers. In the light of developing a method to optimize the design of natural convective micro-heat sinks, the scientific community needs to widen the knowledge of the basics of convective heat transfer at micro-scale. The behavior of the heat transfer coefficient, as well as different heat sink metrics, has to be investigated. There is a number of works focusing on micro-fins, but only few of them investigated their application in a passive, natural convective environment. Shokouhmand and Ahmadpour [15] presented a numerical investigation about heat transfer from a top facing micro-fin array heat sink. They demonstrated that radiation can contribute up to 22% of the total heat transfer: the radiative exchange need to be considered when the heat behavior of micro-scaled heat sinks is analyzed. Kim et al. [16] demonstrated the impossibility of using the macro-fin heat transfer correlations for micro-scaled systems. The authors presented a first important investigation on natural convective micro-fin arrays, proving that the 100 to 200 μm-high fins used in their study could produce an enhancement in the thermal exchange up to 10%. They showed that the orientation effect can be neglected for vertical and horizontal micro-fin arrays and demonstrated that the convective heat transfer increases with increasing the spacing and the temperature difference between heat sink and ambient. Mahmoud et al. [17] investigated the thermal effect of 0.25 to 1.00 mm-high fins on copper heat sinks. In their work, the authors considered an upward facing array, uniformly heated by an electrical mat, with input powers ranging from 0.2 to 1.6 W. Their results showed that the values of convective heat transfer coefficient increased while increasing the fin spacing or decreasing the fin height. In their work, the authors did not take into account the effect of fins thickness on the thermal exchange.

In the present study, different 5 cm-wide squared heat sinks are studied under different power inputs, with the aim of extending the studies of the previous researchers. Firstly, the effects of the fin geometry are investigated for power loads higher than previously considered, in order to give a contribution towards the optimization of geometries for micro-finned heat sinks. In particular, the correlation between thickness and heat transfer is analyzed for the first time and commented. Based on that, a new correlation for determining the Nusselt number in micro-fins application is proposed. Secondly, an experimental comparison between the performance of plate fins and pin fins is reported. The previous micro-fins researches used to consider the same conditions, horizontal upward facing or vertical micro-finned heat sinks. In real applications, instead, the designer might be forced to orientate the heat sinks in different, less-effective directions, such as in downward facing position [4]. For this reason, the third scope of this paper is to report the differences in thermal performance between an upward facing and a downward facing micro-fins array.

2. Experimental apparatus

Each micro-finned heat sink exploited in this study has been produced by a 1.4 mm thick squared wafer, made of undoped silicon and sized 5 cm × 5 cm. Nine different fin geometries are tested and compared with a flat silicon wafer. Two fin types are considered: parallel rectangular plate fins (Fig. 1a) and square pin fins (Fig. 1b). The fins dimensions have then been measured using a microscope and are reported in Table 1, according with the nomenclature shown in Fig. 1. The micro-finned arrays have been firstly designed using a CAD software package and then fabricated through a dicing machine.

A schematic of the experimental setup is shown in Fig. 2 and has been developed similarly to those already referenced in literature [16,17]. The arrays are heated using 10 W flexible heaters (Omega KHLV-202/2.5), bonded through a conductive adhesive (3 M tape 966, 0.18 W/mK). The samples are held in an 8 cm × 8 cm case, made of a 1 cm-thick fiber thermal material