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Experimental and numerical study of micro-pin-fin heat sinks with variable density for increased temperature uniformity

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ABSTRACT

Current technologies for the cooling of high power integrated circuits (IC) chips employ single-phase liquid flow through microchannel heat sinks. The surface temperature in these devices increases along the flow direction, leading to temperature nonuniformities in the cooled device. Mitigation of this temperature nonuniformity, while enhancing the heat exchange along the flow path, has been demonstrated through the use of variable fin density microchannels. This paper demonstrates experimentally and numerically the potential of micro-pin-fin heat sinks as an effective alternative to microchannel heat sinks for dissipating high heat fluxes from small areas. Results from this experimental and numerical investigation demonstrate the ability of variable pin-fin density with offset configurations to reach low thermal resistance coefficients and reduce the surface temperature nonuniformity while presenting low-pressure drops. For the maximum Reynolds number considered in this study (2200), we demonstrate the capacity of the cooling scheme, when submitted to a heat flux of 50 W/cm^2, to reach a pumping to chip power ratio of 0.37%, a thermal resistance coefficient of 0.26 cm^2 K/W and a temperature uniformity along the 5 cm long cooling device of 2 °C.

1. Introduction

The heat fluxes that must be extracted from electronic devices and other applications are increasing in magnitude and the space available for dealing with these loads become, in many cases, increasingly smaller. Liquid cooling technologies have emerged as a viable alternative to traditional air cooling for high power electronic devices. Since *Tuckerman and Pease* [1], microchannel liquid cooling technology has received increased attention, and currently is one of the most active research fields in the technical thermal management literature [2–13]. Microchannels provide high heat transfer coefficients in a compact format, making this solution amenable for integration as liquid cold plates or even embedded microchannels in microelectronic modules.

Steinke and Kandlikar [14] have proposed and studied some passive enhancement techniques for microchannels and mini-channels. Their discussion indicates that the inclusion of some flow disruptions can serve to trip the boundary layer and, importantly, increase the heat dissipation. Offset strip fins were proposed as an alternative for microchannel configurations.

Taking into account the conclusions of [14], many researchers focused on the novel micro-size heat exchanger with pin-fin structures [15–20], and results show that using micro pin-fins is beneficial for the heat transfer rate with high heat flux. Besides, many other researchers [21–26] have experimentally and numerically studied the fluid flow that crosses the micro pin-fins.

Most of the studies listed are focused on the maximum temperature of the cooled device (or the thermal resistance of the cooling device) and the pressure drop, and do not correct the major drawback related to the utilization of constant cross-section microchannel or pin-fins heat sinks, which is the high temperature variation along the flow direction. However, for microelectronics applications, the temperature uniformity of the cooled device has an impact on the reliability of the whole system [27]. For other applications like, for example, dense array CPV (Concentrating PhotoVoltaics) receivers, the temperature non – uniformities impact negatively on both the reliability and the efficiency of the entire system [28–30], making even more significant to reduce them to the minimum possible.

The best results of temperature uniformity have been presented by Hetsroni [31], with a two-phase cooling scheme. But the difficulties involved with predicting Critical Heat Flux still constitute an important

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Nomenclature

A	Heat exchange surface $[m^2]$
d	Diameter of the pin fins $[m]$
D	Fin area density $[-]$
h	Convective heat transfer coefficient $[W\cdot(m^2\cdot K)^{-1}]$
L	Length of the heat sink $[m]$
m	Number of pin fins in a column $[-]$
n	Number of pin fins in a row $[-]$
ΔP	Pressure drop $[Pa]$
P_{chip}	Heat power dissipated by the chip $[W]$
P_{pump}	Pumping power $[W]$
q''	Heat flux $[W/m^2]$
Q	Flow rate $[m^3/s]$
Re_{in}	Reynolds number – calculated at the slot inlet of the device $[-]$
R_t	Global thermal resistance coefficient $[m^2\cdot K/W]$
T_{fluid}	Fluid temperature $[K]$
T	Temperature $[K]$
V	Coolant velocity $[m/s]$

Greek letters

λ	Thermal conductivity $[W\cdot(m\cdot K)^{-1}]$
μ	Fluid dynamic viscosity $[Pa\cdot s]$

Subscripts

in	Inlet
max	Maximum
num	Numeric
wall	Interface solid-liquid

problem and tend to undermine the reliability of this kind of system.

Conventional cooling schemes present constant hA (where h is the convective heat transfer coefficient and A the heat exchange surface) values along the coolant flow path, resulting in temperature non-uniformities (Fig. 1a). For this kind of cooling solutions, the only way to reduce the temperature non-uniformities is to increase the flow rate. But this involves huge increases in the pressure drop and, therefore, of the pumping power. In order to avoid this drawback, the convection thermal resistance must be reduced along the flow path, compensating for the increase in flow temperature, which can also be considered as an additional thermal resistance since the available ($T_{fluid}(x)$-T_{wall}) reduces compared to ($T_{fluid,in}$-T_{wall}) as we progress along the microchannel (Fig. 1b).

With the aim of improving the temperature uniformity while maintaining the overall thermo-hydraulic performance, Rubio-Jimenez et al. [32] [33], proposed a micro pin-fin heat sink with variable fin density as an alternative for cooling the next generation of IC chips. They demonstrated, for a pumping power of 0.04 W/cm^2 and a heat flux of 230 W/cm^2, an overall value of the temperature gradient of 1.63 °C/mm, which was four times lower than the temperature gradient generated in rectangular microchannel heat sinks subject to similar sizes and operating conditions.

Other studies [34–38] focused on hybrid Jet impingement/microchannel (JIMC) cooling devices and validated their capacity to counteract the coolant temperature increase and, therefore, to provide a nearly constant (or even decreasing) temperature distribution of the cooled object along the flow path. This effect is obtained by tailoring, at the design stage, the widths of the channel to the local need of heat extraction capacity (Fig. 2). The slot jet-impingement used as the inlet allows to reduce the coolant flow path and to tailor, by adjusting the slot width, the local heat extraction capacity at the center of the cooling device [39].

The main goal of this paper is to introduce a new hybrid cooling scheme that replaces the longitudinal fins of the microchannels sections by a matrix of pin-fins, named hereafter JIPF_A1. This device takes advantage of the Hybrid jet impingement/microchannels cooling device improvements with respect to conventional microchannels while offering the possibility to vary the heat exchange surface in two directions. In a first step, the new hybrid Jet Impingement/Pin Fin matrix (JIPF) cooling scheme performance is assessed and compared numerically and experimentally with the Hybrid Jet Impingement/Microchannels for a comparable layout, in order to isolate the effect of the geometry of the heat exchange area from its distribution. Once validated, the numerical model is used to assess the impact of the pin fins distribution on the thermo-hydraulic performance in order to identify the key factors for design.

2. Heat sink design and experimental set up description

The JIPF cooling scheme entails two well-differentiated areas. The first corresponds to a cooling system using jet impingement while the second consists of a series of pin-fin rows. To achieve a uniform wall temperature even though the fluid temperature will increase along the flow path, the configuration must be defined to locally adapt the convective thermal resistance.

To increase, along the flow path, the convective heat transfer coefficient, h, and the heat exchange surface, A, the density of pin fins is increased. In addition, the JIPF configuration proposed here leverages the increased h due to the impinging jet. The heat sink design procedure for variable hA with impinging jet is detailed by Riera et al. [38].

To allow comparison between the pin-fin (JIPF) and microchannel (JIMC) cooling schemes, the distribution of rows of pin-fins in this work (Fig. 3) is similar to rows of variable density microchannels in the previous hybrid Jet Impingement/MicroChannels cooling scheme work [38]. The pin-fins are circular with a radius of 100 μm. The spacing between the pin-fins rows decreases from 1.64 mm to 240 μm. This pattern is etched in a silicon wafer (total thickness of 550 μm) by lithography and deep reactive ion etching (DRIE), creating a constant depth (z = 300 μm) pin-fins array.

The schematic design of the experimental test module and its

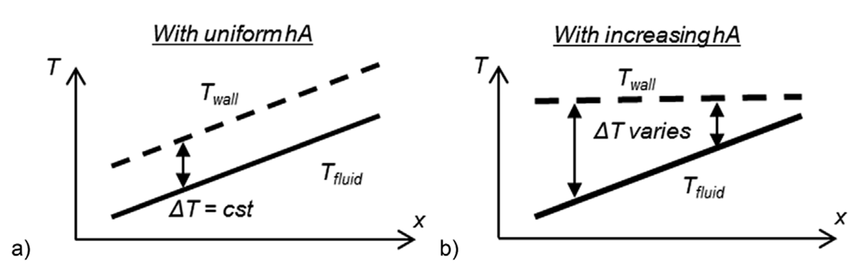

Fig. 1. Temperature uniformity along the flow path (x direction). a) conventional cooling scheme; b) cooling scheme with decreasing thermal resistance along the flow path (increasing hA).