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# Investigation of self-similar heat sinks for liquid cooled electronics

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A B S T R A C T

Electronic systems require cooling devices that are able to deal with high heat-flux capabilities. For this purpose, microchannels are attractive for direct cooling, due to their superior performances. A study on self-similar heat sinks for liquid cooled electronics is presented in this work, where the devices are made from copper, designed for industrial application and for large scale production. Self-similarity refers to the fact that there is a certain similarity and repeatability (or pattern) of the substructures compared with the overall structure. The internal structures, the so called overflow structures (or microchannels), have been designed in order to achieve high heat transfer coefficients. To validate the design and describe the flow characteristics inside the device via analytical solutions is almost impossible, therefore a well known numerical code was employed to have an insight of the thermal-fluid distributions. As can be seen clearly from the simulation, most of the heat is removed in the overflow-structure, on the side of the device adjacent to the source of heat. This paper attempts to analyse a comprehensive list of data as well as plots in a critical manner in order to illustrate the significant characteristics of this type of device. A clear lack in a proper common definition of the heat flux may lead to a misinterpretation of the results, in fact depending on the chosen area where the heat exchange takes place (namely the internal area of the microstructures or the separation surface between the device and the heating source), we can achieve a maximum heat flux of either about 200 W/cm$^2$ or about 700 W/cm$^2$. A very low pressure drop together with a good heat removal capability, make this device suitable for cooling of IGBT chips in power electronic applications.



## 1. Introduction

In electronic devices, thermal management issues play an increasingly prominent role in microelectronic system design, as do the difficulties. The constraints on heat removal are a major factor limiting the performance of a microelectronic system, but the high heat transfer coefficients achievable in microchannels are attractive for direct cooling of electronic systems.

The use of microchannels as a viable cooling solution was first proposed 30 years ago by Tuckerman and Pease [1]. They showed that a single layer microchannel etched directly on a silicon wafer is highly effective for dissipating heat. Using water as a working fluid they demonstrated that these microchannels can remove up to 790 W/cm$^2$ of heat.

The effectiveness of a microchannel device for high heat flux cooling lies in its increased heat transfer coefficient and in a large surface area to volume ratio, and micro heat exchangers have been widely implemented in different sectors of research and industry [2]. State of the art micro-scale convective heat transfer techniques are presented for use in heat sinks.

In chemistry and biological sciences microchannels are used in various microsystems such as micro heat sinks and microreactors, because of their different superior performances compared to conventional size devices.

The recent attention on micro devices has favoured not only the research in the thermal-fluid-dynamics, but also in the field of micro-fabrication techniques, i.e. among others this includes hot-embossing, lithography, etching, micro-mechanical machining and diffusion-bonding.

Several researchers have investigated the possibility of implementing different shapes for the microchannels, ranging from rectangular, to semi-circular, to triangular and so on, both from a fluid-dynamic as well as a manufacturing point of view [2]. Even though, many have been oriented to using simple, easily obtainable shapes.

In this work we are presenting the results of a study on self-similar heat sinks for liquid cooled electronics, made from copper, designed

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**Nomenclature**

| | |
|---|---|
| $A_a$ | surface area, cm$^2$ |
| $c_p$ | specific heat capacity, J kg$^{-1}$ K$^{-1}$ |
| $D$ | hydraulic diameter, m |
| $\overline{h}$ | average heat transfer coefficient, W m$^{-2}$ K$^{-1}$ |
| $k$ | thermal conductivity, W m$^{-1}$ K$^{-1}$ |
| $L_h$ | hydrodynamic entrance length, m |
| $L_t$ | thermal entrance length, m |
| $\dot{m}$ | mass flow rate, kg h$^{-1}$ |
| $\Delta p$ | pressure difference, mbar |
| Pr | Prandtl number |
| $\dot{Q}$ | thermal power, W |
| $q$ | heat flux, W cm$^{-2}$ |
| $\mathrm{Re}_D$ | Reynolds number based on the hydraulic diameter |
| $T$ | temperature, K |
| $\Delta T$ | temperature difference, K |
| $\nabla T$ | temperature gradient, K |
| $\vec{U}$ | velocity vector, m/s |
| $\Delta x$ | distance, m |
| $\delta_t$ | thermal boundary layer thickness, m |
| $\vartheta$ | intersection angle between velocity and temperature gradient |
| $\rho$ | fluid density, kg m$^{-3}$ |

*Subscripts*

| | |
|---|---|
| $a$ | 1,2 smaller and larger area considered |
| cs | cross section |
| in | inlet |
| out | outlet |
| $b$ | bulk |
| bl | block |
| $s$ | surface |
| $w$ | wall |

for industrial application and for large scale production. Here self-similarity refers to the fact that there is a certain similarity and repeatability (or pattern) of the substructures compared with the overall structure. In fact, as per Fig. 3, a main channel drives the water to a set of sub-channels and then from these to the overflow structures (microchannels, Figs. 1 and 2). As it is almost impossible to validate the design and describe the flow characteristics inside the device via analytical solutions, a well-known numerical code was employed to provide an insight of the thermal-fluid distributions. It is clear from the simulation that even if copper is characterized by high thermal conductivity, most of the heat is removed, in the overflow-structure, on the side of the device adjacent to the heat source.

It should be highlighted that copper was chosen because of its superior thermal conductivity, therefore other solutions could lead towards different materials, see for instance [3] where ceramic was used. Other possible approaches to materials and manufacturing processes may be also found in Ref. [4].

This paper attempts to analyse a comprehensive list of data as well as plots in a critical manner in order to illustrate the significant characteristics of this type of device. Emphasis is put on the validity of conventional ways used to define the heat flux, since many various micro-devices with different characteristics are employed in the industry sector, a not easy task emerges when trying to compare the results.

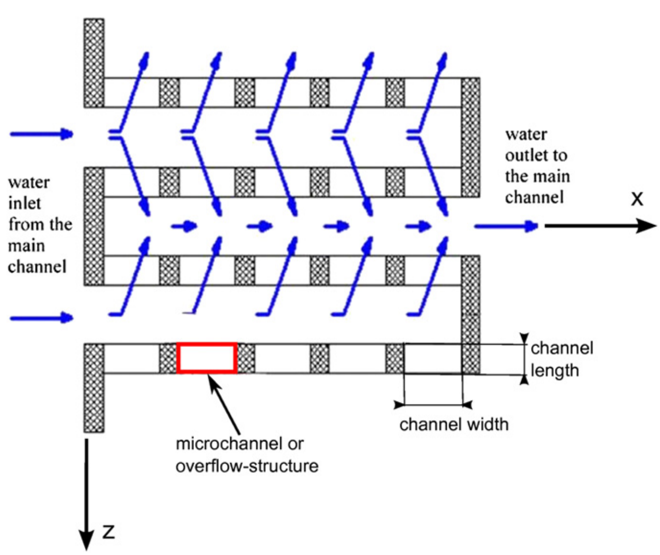


**Fig. 1.** Schematic of the microstructure arrangement and the flow pattern; the actual number of microchannels per row is greater than those shown in this sketch.

## 2. Physical considerations and manufacturing

The internal structures where the most part of the active cooling takes place has been designed in order to achieve high heat transfer coefficients. Remarkably, using short overflow structures (identified as microchannels) it is possible to have a thermal and hydrodynamic developing flow where high thermal gradients are present, in fact as it has been pointed out by different authors [5–7] that reducing the flow length and increasing the number of passages is advantageous in limiting the pressure drop and increasing the Nusselt number for laminar regimes [8].

Considering the energy equations relative to a 2-D boundary layer and 1-D heat conduction re-arranged as shown in Ref. [9]:

$$\rho c_p \int_0^{\delta_t} (\vec{U}\cdot\nabla T)\mathrm{d}y = -(k\partial T/\partial y)_{y=0} = q_w \quad (1)$$

can provide an inside perspective of the manner in which heat is exchanged in a microchannel. Since a fundamental parameter in this equation results in the dot product of the velocity vector $\vec{U}$ and the gradient of the temperature $\nabla T$ (i.e. $\vec{U}\cdot\nabla T = |U||\nabla T|\cos\vartheta$),

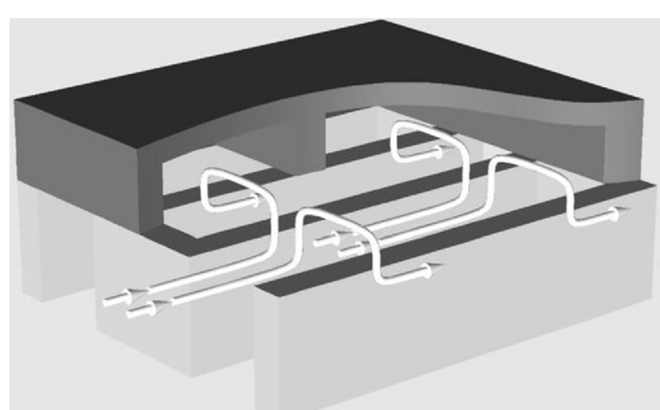

**Fig. 2.** Sketch of the microstructure arrangement and flow pattern in the microstructures.

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