



# Numerical investigation and sensitivity analysis of manifold microchannel coolers

Lauren Boteler<sup>a,b,\*</sup>, Nicholas Jankowski<sup>a</sup>, Patrick McCluskey<sup>b</sup>, Brian Morgan<sup>a</sup>

<sup>a</sup> Army Research Laboratory, Adelphi, MD, United States

<sup>b</sup> University of Maryland, College Park, MD, United States

## ARTICLE INFO

### Article history:

Received 30 December 2011

Received in revised form 24 July 2012

Accepted 25 July 2012

Available online 23 September 2012

### Keywords:

Manifold microchannel

Heat sink

Thermal resistance

Power packaging

Numerical

## ABSTRACT

This paper presents a numerical investigation of a single-phase manifold microchannel cooler (MMC) heat exchanger demonstrating a reduction in fluid pressure drop while improving chip-temperature uniformity. This modeling work includes the entire manifold length with multiple microchannels, whereas previous models have only focused on individual microchannels, ignoring complex manifold effects. Computational Fluid Dynamic (CFD) models were used to identify the impact of varying both the manifold and microchannel fin and channel dimensions, and a sensitivity analysis was performed with respect to system pressure drop, rise in device temperature, and thermal uniformity. This modeling work demonstrated both large velocity gradients between microchannels, as well as fluidic swirling in the microchannels that significantly improved the heat transfer coefficient. These results are absent from unit-cell type models. The results of the full MMC model showed significantly improved chip-temperature uniformity when large (approximately 10X) differences in velocity occurred between microchannels. The simulations also showed that, for equivalent thermal performance, the MMC design resulted in a 97% reduction in system pressure drop when compared to an equivalent straight microchannel cooler. Finally, the numerical pressure drop results were compared to a simpler, one-dimensional approximation based on the Hagen–Poiseuille equation. While under-predicting total pressure drop, the analytical equation does capture prevailing trends of the effects of channel dimensions on the pressure drop and can be used for rapid evaluation of numerous tradeoffs from a system perspective.

Published by Elsevier Ltd.

## 1. Introduction

The electronics industry is moving to smaller products with increased functional density. This equates to electronics with higher heat generation requiring more effective cooling. Power electronics have heat fluxes approaching  $1000 \text{ W/cm}^2$  [1]. Without proper cooling, the increased heat fluxes will result in higher device operating temperatures, which can adversely affect device performance [2]. These high heat fluxes also require the use of forced convection liquid cooling [3]. Microchannel systems are a desirable cooling solution because they have been shown to reduce overall system size and improve the heat transfer coefficient [4]. But the two disadvantages to a microchannel system are typically the high pressure drop caused by small hydraulic diameter channels and non-uniform cooling caused by the fluid absorbing heat along the length of the channel.

Many researchers have looked into ways of reducing these effects: multi-layered microchannel heat sinks [5,6], single plane manifold configurations [7,8], and fractal channels [9,10]. While

each of these designs looks to improve the problems of microchannel cooling, they each have disadvantages. The multi-layered microchannel heat sink still has high pressure drops due to the small hydraulic diameter channels and both the single plane manifold and the fractal channels have much of the heated surface cooled by lower performance macrochannels instead of microchannels.

The solution analyzed in this paper for solving the microchannel problems is the manifold microchannel cooler (MMC) [11] shown in Fig. 1(a), with the dashed box indicating the active cooling area. The fluid volume is represented by the non-transparent grey volume and the solid volume is shown in the figure as partially transparent. The fluid flow path is shown in both Fig. 1(a) and (c). The MMC incorporates a two-stage flow designed to take advantage of both large and small channels. The fluid flows in through large, long channels located away from the heated surface (manifold channels), then is forced through much smaller perpendicular channels in contact with the heated surface (microchannels), and then flows out through another large manifold channel. This design reduces total flow restriction since the majority of the flow occurs in the larger manifold channels. It also maintains the cooling potential of microchannels since they can cover the entire heated surface. The design also improves chip temperature uniformity by reducing the effects of heating along the microchannel length. This

\* Corresponding author. Present address: Army Research Laboratory, 2800 Powder Mill Rd, Bldg 207, Adelphi, MD 20783, United States. Tel.: +1 301 394 0970.

E-mail address: [lauren.m.boteler.civ@mail.mil](mailto:lauren.m.boteler.civ@mail.mil) (L. Boteler).

## Nomenclature

$D_h$	hydraulic diameter (m)	$\Delta p_{manifold}$	total manifold pressure drop (Pa)
$H$	rectangular channel height (m)	$\Delta p_{manifold\_in}$	inlet manifold pressure drop (Pa)
$L$	channel length (m)	$\Delta p_{manifold\_out}$	outlet manifold pressure drop (Pa)
$L_{chip}$	length of chip (m)	$\Delta p_{microchannel}$	microchannel pressure drop (Pa)
$L_{entrance}$	manifold entrance length (m)	$q''$	heat flux ( $W/m^2$ )
$L_{exit}$	manifold exit length (m)	$Q$	fluid volumetric flow rate (mL/min)
$m_w$	microchannel width ( $\mu m$ )	$Q_{flow}$	volumetric flow rate (mL/(min $\mu m$ ))
$m_f$	microchannel fin width ( $\mu m$ )	$Q_{system}$	system volumetric flow rate (mL/(min $\mu m$ ))
$m_h$	microchannel height ( $\mu m$ )	$\Delta T_{chip}$	rise in chip temperature ( $^{\circ}C$ )
$M_w$	manifold width ( $\mu m$ )	$\Delta T_{fluid}$	rise in fluid temperature ( $^{\circ}C$ )
$M_f$	manifold fin width ( $\mu m$ )	$\mu$	dynamic viscosity (Pa s)
$M_h$	manifold height ( $\mu m$ )	$v$	velocity (m/s)
$N_{ch}$	number of microchannels	$v_{in}$	manifold inlet velocity (m/s)
$\rho$	density ( $kg/m^3$ )	$v_{microchannel}$	microchannel velocity (m/s)
$\Delta p$	system pressure drop (Pa)	$W$	rectangular channel width (m)
$p_{in}$	inlet pressure (Pa)		
$p_{out}$	outlet pressure (Pa)		

can reduce the chance of mechanical failures caused by in-plane spatial temperature gradients. The primary drawback of the MMC desing is the additional complexity and volume associated with the addition of the manifold channels.

The critical dimensions for the MMC are shown in Fig. 1(b) with “ $m$ ” referring to the microchannel dimensions and “ $M$ ” referring to the manifold dimensions. The three subscripts:  $h$ ,  $f$ , and  $w$  refer to the height, fin width and channel width, respectively.

There have been several numerical studies of the MMC design that have verified the benefits of the design. Harpole and Eninger [11] were the first to propose the MMC design through a numerical study which looked to optimize the microchannel dimensions. However, their study did not look to optimize the effect of the manifold channels or consider their effect on the pressure drop. Copeland published a numerical study on the MMC design using a single microchannel unit cell [12] which is highlighted by the boxed area in Fig. 1(c). The unit cell includes a single half-channel of a single microchannel section with the fluid flowing in and out of the bottom, symmetry is assumed on all sidewalls, and a constant velocity and temperature assumption is applied at the inlet. A number of models were run to see the effects of various microchannel parameters on the performance. Poh and Ng [13,14] expanded on the same unit cell model as Copeland, showing similar results.

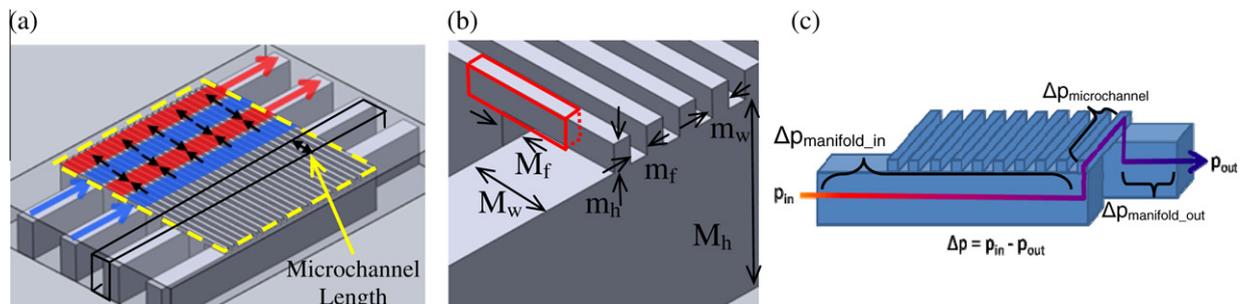
Each of the previous models has been limited to the microchannel unit cell, which fails to capture the effects of the manifold portion of the device. Another numerical study by Ryu did include the manifold portion under a single microchannel unit cell [15], but

did not look into the effects of pressure drop or flow maldistribution. Additionally, the work by Bejan and Errera [16] presented an analytical solution to optimizing a 2D array of fractal type channels in terms of both thermal performance and pressure drop. While the geometry is different, this is another valid approach to optimizing geometries if it was expanded to 3D. To the authors’ knowledge, no modeling has been done to date looking at the entire length of a manifold to see the effects the manifold has on the plurality of channels.

This work presents the first modeling of a full MMC structure to elucidate the complicated relationships between dimensions, thermal performance, and pressure drop. Primary performance metrics remain chip temperature and pressure drop which are typically competing factors due to the fact that smaller hydraulic channels typically have higher thermal performance but increased pressure drop. The following sections first develop analytical expressions to approximate the pressure drop in MMC systems to guide the approximate design space, followed by a complete numerical solution for a single geometry. Finally, a parametric study is performed on various MMC dimensions.

## 2. Analytical pressure drop calculations

Reducing the system pressure drop is critical to improving the system performance as it will determine the necessary pump size. In order to estimate the pressure drop in a MMC system analytically, we have developed a method based on the Hagen–Poiseuille



**Fig. 1.** Schematics of the (a) overall MMC structure with the dashed box indicating the actively cooled area, the top arrows showing the fluidic path, the black region showing the modeled portion, and the microchannel length used in the models pointed out (b) MMC structure indicating the critical dimensions with the solid grey area representing the fluid (c) fluidic volume of the modeled structure showing the flow paths and the three pressure drops used to calculate the analytical pressure drop approximation.

متن کامل مقاله

دریافت فوری ←

**ISI**Articles

مرجع مقالات تخصصی ایران

- ✓ امکان دانلود نسخه تمام متن مقالات انگلیسی
- ✓ امکان دانلود نسخه ترجمه شده مقالات
- ✓ پذیرش سفارش ترجمه تخصصی
- ✓ امکان جستجو در آرشیو جامعی از صدها موضوع و هزاران مقاله
- ✓ امکان دانلود رایگان ۲ صفحه اول هر مقاله
- ✓ امکان پرداخت اینترنتی با کلیه کارت های عضو شتاب
- ✓ دانلود فوری مقاله پس از پرداخت آنلاین
- ✓ پشتیبانی کامل خرید با بهره مندی از سیستم هوشمند رهگیری سفارشات