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Research Paper

Multi-objective optimization of a double-layered microchannel heat sink with temperature-dependent fluid properties

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HIGHLIGHTS

- Multi-objective optimization of a double-layered MCHS of rectangular wedge shape was performed.
- The narrower microchannel design yielded the lower thermal resistance at the higher pumping power.
- A 14.9% change in thermal resistance was accompanied by a 64.1% change in pumping power.
- The pumping power was lowered significantly with the increase in the heat flux.
- The lowest thermal resistances leaded to the lowest maximum temperatures at the substrate bottom.

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ABSTRACT

Multi-objective optimization of a microchannel heat sink with a rectangular wedge-shaped cross section was performed in this work. The optimization was performed by a multi-objective genetic algorithm using three-dimensional conjugate heat transfer analysis with variable thermo-physical properties of the coolant (water). Response surface approximation was used to approximate the objective function to reduce computing time. Two geometric variables related to the channel cross section and a ratio of flow rates in the upper and lower channels were selected as design variables for the optimization. Thermal resistance and pumping power were considered as the objective functions. The design space was explored through a parametric study, and Latin hypercube sampling was used for the selection of the design points. The optimizations were performed for three different heat fluxes: 1×10^6, 2×10^6, and 3×10^6 W/m^2. Pareto-optimal fronts representing the trade-offs between the performance parameters were obtained for the selected heat fluxes, which yielded important results for the design of microchannel heat sinks.

1. Introduction

With the advancements in microelectromechanical systems, very large scale integrated technologies and the demand for miniaturization have increased the packing density and heat generation in micro-devices. Microchannel heat sinks (MCHSs) have benefitted from rapid growth in cooling technologies for microprocessors and microelectronic components, where the heat flux is expected to exceed 100 W/cm^2 [1,2].

After the foundational work of Tuckerman and Pease [3], considerable attention has been paid in understanding the governing parameters that affect the performance and operation of MCHSs [4–7]. Hassan et al. [8] published a thorough review of the progress of research in the field of MCHSs. They examined studies on coolant types, coolant phases, surface roughness, boiling instabilities in two-phase flow, microchannel geometries, and fluid properties. Mokrani et al. [9] performed an experimental investigation of a rectangular microchannel in the hydraulic diameter range of 100 µm to 1 mm, and an aspect ratio range of 60 to 600. They calculated the bulk Nusselt number and compared their results with classical channel flow theory. Natrajan and Christensen [10] applied a two-color laser-induced fluorescent thermometry method for measuring the instantaneous fluid temperature of laminar flow in microchannels. This non-intrusive and spatially resolved technique was used for the estimation of local Nusselt numbers in smooth and rough wall MCHSs. Other experimental studies [11,12] were also performed for enhancement of the Nusselt number.

The successful design of MCHSs relies on understanding the physics of the fluid flow and heat transfer. Numerical analysis has helped to find the effects of various parameters on the performances of MCHSs. Toh et al. [13] performed a numerical analysis for the prediction of heat transfer characteristics in MCHSs and compared the predicted results with the experimental results of Tukerman and Pease [3]. Chen et al. [14] developed a three-dimensional (3-D) numerical model to study heat transfer and fluid flow in triangular, rectangular and trapezoidal-shaped microchannels.

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Their results showed that the triangular microchannel heat sink has the highest thermal efficiency among the studied shapes.

Works on various circular and non-circular microchannel geometries are available in the literature, which include rectangular, triangular, trapezoidal, and offset fan-shaped channels [15]; grooved channels [16]; and I- and U-channels [17]. Ding and Manglik [18] reported analytical solutions for fully developed flow in triangular, trapezoidal, sine, double sine, rhombic, and polygonal ducts. Tamayol and Behrami [19] developed an analytical solution to predict the velocity distribution and pressure drop in fully developed laminar flow in hyper-elliptical and polygonal mini-channels and microchannels, and compared them with experimental data. Their study covers a wide variety of cross sectional shapes: circle, ellipse, rectangle with rounded corners, rhombus, star-shape, equilateral triangle, square, pentagon, and hexagon. Chen et al. [20] investigated numerically the thermal and hydrodynamic characteristics of a constructal tree-shaped mini-channel heat sink. The performance of this heat sink was more than twice that of a traditional serpentine flow pattern heat sink.

The concept of microchannel cooling was further extended from a single layer to a double layer by Vafai and Zhu [21]. They concluded that a double-layered MCHS with a counterflow arrangement improved the performance of a microchannel significantly in terms of thermal resistance and pressure drop. The thermal performance of a stacked MCHS was characterized experimentally and numerically by Wei et al. [22]. They examined the effects of coolant flow rate, the flow ratio, and non-uniform heating in parallel and counter flow configurations on heat transfer performance. Their experimental results show that improvement in the overall cooling performance of a stacked microchannel can be on the order of 0.09 °C/Wcm^2. Levac et al. [23] demonstrated that a double-layered counterflow arrangement is superior to a single-layered design in terms of uniformity of the temperature under the chip at the same total mass flow rate of the coolant. Xie et al. [24] performed a comparative study on the thermal performance between parallel flow and counterflow double-layered wavy MCHSs. They examined the effects of the wave amplitude and volumetric flow ratio on thermal resistance and pressure drop.

In the past decade, many studies have been performed on the optimization of heat exchanging devices using various optimization algorithms [25–28]. Li and Peterson [29] introduced geometric optimization to the design of a MCHS to enhance heat transfer. Meysam and Pascal [30] optimized a thermal microfluidic chip. They studied the effect of geometry parameters on the thermal response at the interface of a microfluidic chip, and presented results in the form of design charts. Husain and Kim [31,32] examined thermal optimization of MCHSs with and without ribs, and showed that the thermal resistance of the MCHS was considerably reduced through optimization. Ansari et al. [33] performed a shape optimization of a staggered grooved MCHS using a multi-objective evolutionary algorithm to reduce thermal resistance and pumping power, and compared the results with those of a smooth microchannel. Hung et al. [34] proposed a combined optimization approach based on a simplified conjugate-gradient method and a three-dimensional (3-D) porous heat sink model for maximizing the thermal performance of MCHSs.

The thermal performance of MCHSs deteriorates significantly due to temperature non-uniformity, which causes hot spots. Mahajan et al. [35] reported that the local power density at a hot spot on a microchip reached 300 W/cm^2, and that the hot spot produces thermal stress in the chip that impacts the performance and reliability of the system. Thus, it is necessary to develop new methodologies that guarantee better heat removal capability. Previous studies reveal that the bulk temperature rise inside a microchannel can be governed by increasing the coolant flow at a penalty of increased pressure drop. Thus, a high pressure drop across the channel is another consideration in the design of MCHSs. A larger pressure drop leads to higher pumping power, making the system noise and bulky. Hence, the key to maintaining high thermal performance without excessive pressure drop is to choose appropriate channel geometry and to optimize the geometric parameters.

In the present study, a double-layered MCHS was optimized based on 3-D Navier–Stokes analysis. Two geometric parameters and one flow parameter were selected as design variables for optimization. A multi-objective optimization was performed using response surface approximation (RSA) for the objective functions i.e., thermal resistance and pumping power for three different heat fluxes.

2. Numerical analysis

2.1. Flow configuration

Fig. 1 shows a schematic of the double-layered MCHS and the computational domain. The dimensions of the MCHS under consideration are 10,000 × 10,000 × 260 μm ($L \times W_{total} \times H$). A uniform heat flux was applied at the bottom of the silicon substrate, and the heat was removed by the coolant flowing from the inlet to the outlet. The computational domain is one-half of a unit cell of a microchannel array, as indicated in Fig. 1. The cross-sectional geometry of the

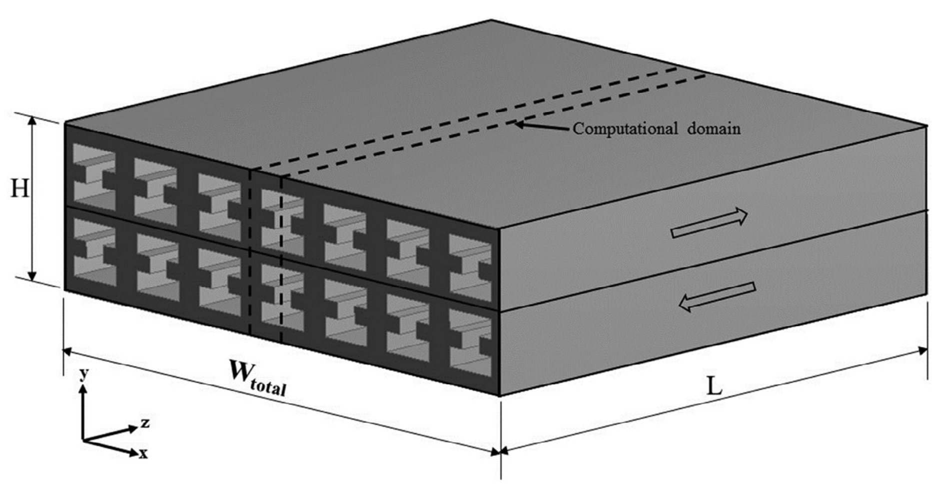

Fig. 1. Schematic of microchannel heat sink and computational domain.