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Optimization of thermal resistance and bottom wall temperature uniformity for double-layered microchannel heat sink

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ABSTRACT

In this paper, a three-dimensional solid–fluid conjugate model coupled with a simplified conjugate-gradient method was employed to optimize the performance of double-layered microchannel heat sinks. Channel number, channel width, bottom channel height, and bottom coolant inlet velocity were selected as search variables to achieve the optimal heat sink performance. Firstly, two single-objective optimizations based on different objective functions (one is the maximum temperature change on the bottom wall $\Delta T_{w,b}$ and the other is the overall thermal resistance R) were performed at a constant pumping power. Subsequently, the effects of total pumping power on the optimal $\Delta T_{w,b}$ and R were analyzed, and the optimal search variables at various pumping powers were obtained. For single-objective optimization with the objective function of $\Delta T_{w,b}$, $\Delta T_{w,b}$ is respectively decreased by 6.01, 5.29, and 2.99 K when compared with three original designs. For the objective function of R, however, R is respectively decreased by 36.51%, 15.10%, and 16.67%. The results also indicate that R and $\Delta T_{w,b}$ cannot achieve their optimal values simultaneously by the two single-objective optimizations. Thus, a multi-objective optimization was carried out, which demonstrates that when a set of desirable values of $\Delta T_{w,b}$ and R is required by designers, the present multi-objective optimization could meet this requirement.

1. Introduction

Over the last several decades, heat flux is ever-increasing with rapid development of microelectronic devices. When the heat flux reaches up to 100 W cm^{-2}, the conventional cooling technology is failed to meet the requirement of thermal removal as expected. Fortunately, the microchannel heat sink (MCHS) proposed by Tuckerman and Pease [1] in 1981 can endure a heat flux as high as 790 W cm^{-2}, which becomes a significant way for thermal management of microelectronic devices and attracts a great deal of attention [2–20].

The MCHS is composed of many parallel micro channels. Because coolant flows in a single direction, temperature increases rapidly along the streamwise direction, leading to a poor uniformity of temperature distribution on the bottom wall of the heat sink. The large temperature rise results in undesirable thermal stresses in microelectronic devices due to the mismatch of thermal expansion coefficient among different materials, and hence reduces reliability and shortens lifetime of the microelectronic devices. In addition, in microelectronic devices, thermal instability and thermal breakdown could occur at high-temperature hotspots.

To weaken streamwise temperature rise of the coolant. Vafai and Zhu [21] proposed a new design concept of double-layered microchannel heat sink (DL-MCHS), where two single-layered microchannel heat sinks (SL-MCHS) are staked one on top of the other. Following Vafai and Zhu's work, extensive studies focused on the DL-MCHS were conducted [22–37], which further justified the results indicated by Vafai and Zhu [22–24], demonstrated that the channel number [25,26], aspect ratios of the top and bottom channels [25–29], channel-to-pitch width ratio [25], and inlet velocities of both layers [26,30] have important effects on the DL-MCHS, and obtained the optimal values of these parameters. In these studies [25–30], when the effect of a specific parameter on the DL-MCHS was examined, the other parameters remained unchanged. However, because there exists strong coupling among various parameters, the channel number, aspect ratios, channel-

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to-pitch width ratio, and inlet velocities influence the performance of the DL-MCHS together rather than separately. Consequently, some researchers simultaneously optimize the multiple parameters influencing the performance of the DL-MCHS to obtain the optimal geometry structure and operation condition. Multi-parameter optimization can be divided into single-objective optimization and multi-objective optimization.

In the single-objective optimization, Chong et al. [31] employed the direct search method and thermal resistance network model to optimize the SL-MCHS and DL-MCHS under the constant pressure drop. Wei and Joshi [32] used box optimization method (BOM) to carry out the optimization research with the constraint of invariable total pumping power. Jeevan et al. [33] incorporated genetic algorithms (GA) and BOM into a two-dimensional heat transfer model of the DL-MCHS, respectively, to optimize the heat sink performance at a constant pumping power. Their results showed that the GA required far less iteration time compared to the BOM to complete the optimization. Subsequently, Jeevan et al. [34] adopted the same GA with three different heat sink models to optimize the DL-MCHS performance. They found that the results obtained from one-dimensional finite element method (FEM) analysis agree well with those obtained from the thermal resistance network model, however, the two-dimensional FEM analysis results in lower thermal resistance. Therefore, they concluded that the importance of considering the conduction in two dimensions in the microchannel is highlighted. Hung et al. [35] and Lin et al. [36] adopted a simplified conjugate-gradient method (SCGM) with a three-dimensional solid–fluid conjugate model to optimize the flow and heat transfer characteristics of the DL-MCHS. In Hung et al.'s optimization, only geometric parameters of the heat sink are chosen as optimized variables with constraint condition of constant pumping power. As an improvement, however, the flow rate assignment in the top and bottom layers are also optimized besides geometric parameters in Lin et al.'s work, and optimizations are implemented at constant pumping power, constant pressure drop through the heat sink, and constant coolant volumetric flow rate, respectively.

In the above-mentioned studies, only the overall thermal resistance was selected as objective function to search for the optimal heat sink performance. The overall thermal resistance represents how much amount of heat can be removed by the heat sink under a certain temperature difference. However, it cannot evaluate the temperature uniformity on the bottom wall of the heat sink. Compared with the SL-MCHS, the main advantages of the DL-MCHS consist in the better uniformity of temperature distribution on the bottom wall. Considering that the temperature uniformity can be evaluated by the maximum temperature change on the bottom wall, it is necessary to carry out the optimization with the maximum temperature change as the objective function. Unfortunately, such optimizations have not been reported in the open literature.

Few works concerned the multi-objective optimization of the DL-MCHS. Pang et al. [37] combines a multiple objective genetic algorithm with a computational fluid dynamics code to optimize the DL-MCHS. The temperature uniformity, entropy production, maximum temperature of heat sink and total pumping power were chosen as optimized targets simultaneously. In Pang et al.'s work, the dimensions and sizes of the top and bottom channels were assumed to be the same and the optimization was performed at a fixed inlet velocity. In fact, the top and bottom channels should have different sizes and inlet velocities for the optimal design because only the bottom layer is directly attached to a heated surface, so that the amount of heat dissipated by two layers of channels is quite different. Furthermore, to fairly compare the heat sink performance, the pumping power should be fixed during the optimization.

In the present study, a multi-objective and multi-parameter optimization approach was developed, which coupled the SCGM algorithm with a three-dimensional solid–fluid conjugate model of the DL-MCHS. In the optimization, channel number N, channel width W_c, bottom channel height H_{c1}, and bottom coolant inlet velocity u_{in1} were selected as search variables. To improve the temperature uniformity on the bottom wall and reduce the overall thermal resistance, a weighted average function of overall thermal resistance and maximum bottom wall temperature change was used as the multi-objective function. Two single-objective optimizations with objective function of maximum bottom wall temperature change or overall thermal resistance were firstly performed at a constant pumping power, respectively. Then, the dependence of the optimal search variables on pumping power was examined for the two single-objective optimizations. Finally, an optimization case was performed to demonstrate that preassigned overall thermal resistance and bottom wall temperature change can be achieved simultaneously by multi-objective optimization.

2. Model

2.1. Geometry structure of heat sink

Fig. 1 shows the schematic of DL-MCHS. The heat sink has dimension of $L_x = 10$ mm, $L_z = 10$ mm, and $L_y = 1.20$ mm and is composed of two layers of microchannel. The two layers have the same channel number of N and rib number of $N + 1$. The widths are both W_c for the top and bottom channels. The height is H_{c1} for

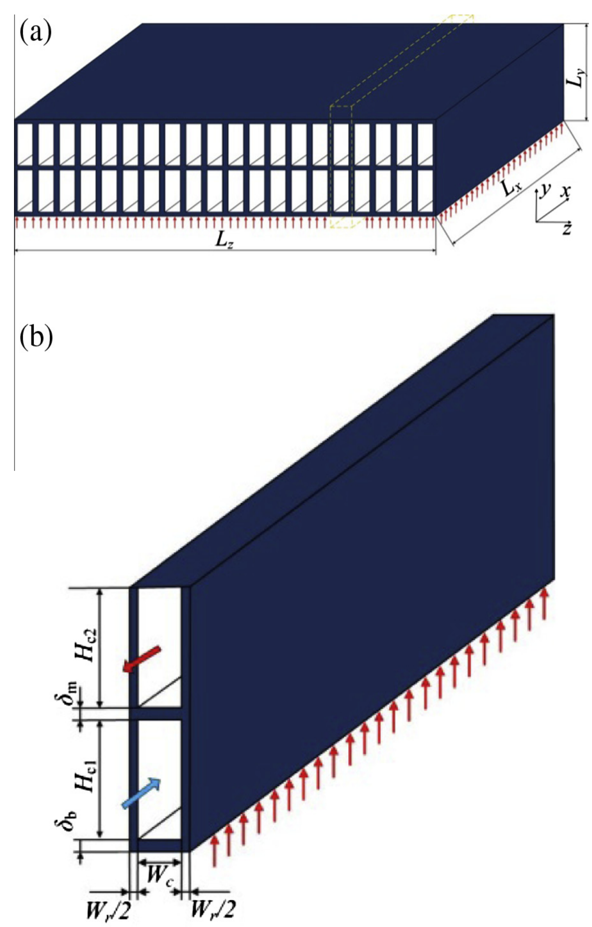

Fig. 1. Schematic of double-layered microchannel heat sink: (a) heat sink; (b) symmetric unit.