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Thermodynamic analysis of the effect of channel geometry on heat transfer in double-layered microchannel heat sinks

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ABSTRACT

Novel double-layered microchannel heat sinks with different channel geometries in each layer (Structure 2 for short) are designed to reduce pressure drop and maintain good heat transfer performance, which is compared with structure 1 (the same of complex channel geometry in each layer). The effect of parallel flow, counter flow and different channel geometries on heat transfer is studied numerically. Moreover, the essence of heat transfer enhancement is analyzed by thermodynamics. On one hand, the synergy relationship between flow field and temperature field is analyzed by field synergy principle. On the other hand, the irreversibility of heat transfer is studied by transport efficiency of thermal energy. The results show that the temperature distribution of counter flow is more uniform than that of parallel flow. Furthermore, heat dissipation and pressure drop of structure 2 are both better and lower than that of structure 1. Form the viewpoint of temperature distribution, structure C2 (i.e., counter flow with rectangular channels in upper layer and complex channels in bottom layer) presents the most uniform bottom temperature for microelectronic cooling. However, comprehensive heat transfer performance of structure P2 (i.e., parallel flow with rectangular channels in upper layer and complex channels in bottom layer) shows the best from the viewpoint of thermodynamics. The reasons can be ascribed to the channel geometry of structure P2 can obviously improve the synergy relationship between temperature and velocity fields, reduce fluid temperature gradient and heat transfer irreversibility.

1. Introduction

The key problem in microchannel heat sinks is to avoid the "hot spot" in the heating film [1]. With the increasing heat dissipation in microelectronic devices, it must be removed efficiently and quickly. Otherwise, the work performance of microelectronic devices will be influenced. Therefore, heat remove in microelectronic devices with high heat flux become to be the most concerned problem in worldwide. Double-layered microchannel heat sinks are one of the effective methods to remove high heat flux. Vafai and Zhu [2] firstly presented the concept of double-layered microchannel heat sinks, as shown in Fig. 1. The heat transfer performance of them was better and pressure drop was substantially lower than that of single-layered microchannel heat sinks under the same heat transfer area and channel dimensions. The most problem is uneven distribution of thermal stress in double-layered microchannel heat sinks. Channel geometry and flow manner will influence it.

At present, lots of researches focus on the same geometry in each layer, i.e., both rectangular channels or complex structure channels. However, for high heat flux, double-layered microchannel heat sinks with complex structure show better heat transfer performance but the corresponding pressure drop will increase. Moreover, heat remove in bottom layer is higher than that of in upper layer. Double-layered microchannel heat sinks with a rectangular wedge-shaped cross section in each layer was conducted by Kulkarni et al. [3]. It indicated that the thermal resistance was lower and pumping power was higher than that of corresponding dimension of rectangular microchannel. Xie et al. [4] investigated both parallel and counter flow with the same channel geometry in double-layered microchannel heat sinks. The results showed that heat remove from bottom layer was higher than that from upper layer, namely heat dissipation of bottom layer was better. The similar phenomenon was also observed by Leng et al. [5]. In our previous works [6,7], we also obtained the similar behavior of heat dissipation in bottom layer. Therefore, to avoid uneven distribution of thermal stress, a novel geometry of double-layered microchannel heat sinks with rectangular channels in upper layer and complex channels in bottom layer is presented.

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Nomenclature

A_{ch}	heat transfer surface [m]
$c_{p,f}$	specific heat [J/(kg K)]
D_h	hydraulic diameter [m]
f	fanning friction factor
H_b	baseplate of the microchannel heat sink [m]
H_{ch}	height of channel [m]
h	heat transfer coefficient [W/(m^2 K)]
L_{ch}	length of the channel [m]
Nu	Nusselt number
N	channel number
Δp	pressure drop [kPa]
PP	pumping power [W]
Q	heat input [W]
Re	Reynolds number
q_w	heat flux [W/m^2]
T_b	average bottom temperature [K]
T_f	average fluid temperature [K]
T_w	average temperature of heating film [K]
u_m	average inlet velocity [m/s]
W_{ch}	channel width [m]

Greek symbols

α_c	aspect ratio
β	field synergy angle
λ_f, λ_s	thermal conductivity of fluid and solid [W/(m K)]
μ_f	dynamic viscosity [Pa s]
ρ_f	fluid density [kg/m^3]
η	thermal enhanced factor
η_t	transport efficiency of thermal energy

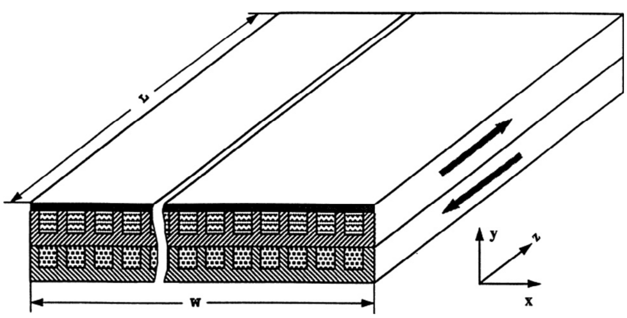

Fig. 1. Schematic of double-layered microchannel heat sinks firstly presented by Vafai and Zhu [2].

Apart from channel geometry, flow manner also obviously influences temperature distribution in double-layered microchannel heat sinks. Parallel flow and Counter flow are the most popular flow manners studied by many researchers. Leng et al. [8] presented a double-layered microchannel heat sink with truncated top channels. They found that the new design with counter flow had more uniform bottom temperature and lower thermal resistance. A double-layered microchannel heat sink with tapered channels presented by Osanloo et al. [9] was investigated the characteristic of flow and heat transfer under counter flow as well.

Thermodynamics analysis aims to investigate the essence of heat transfer enhancement. The concept of field synergy principle based on the second law of thermodynamics was firstly presented by the team of Guo et al. [10,11]. They pointed out that the convective heat transfer phenomenon was related to the synergy degree between velocity field and temperature field. Thus, the synergy degree can be evaluated by heat transfer synergy angle or filed synergy number. Afterward, the principle can be use to explain the essence of various convective heat transfer phenomena. For example, the case of flow and heat transfer in shell and tube heat exchanger [12], impingement jet [13] and vortex generators in a rectangular channel [14] etc. In addition, a new concept of transport efficiency of thermal energy presented by Liu et al. [15] was derived from the second law of thermodynamics. It can be evaluated the irreversibility in heat transfer process.

In view of previous studies to design double-layered microchannel heat sinks, most studies were concentrated on the same channel geometry in each layer. However, these channel geometries showed good heat transfer performance with corresponding high pressure drop. How to design one channel geometry with good heat transfer performance and relative low pressure drop? The main aim is to design channel geometry to lessen the pumping power and improve heat transfer performance as well as increase heat dissipation. Therefore, a novel design of different channel geometry in each layer (structure 2 for short) is designed, namely rectangular channels in upper layer and complex channel in bottom layer. Meanwhile, double-layered microchannel heat sinks with complex structure in each layer are used for comparison (structure 1 for short). Then, the effect of channel geometry of parallel flow and counter flow on heat transfer performance in double-layered microchannel heat sinks is investigated respectively. Finally, based on field synergy principle and transport efficiency of thermal energy, thermodynamic analysis are used to investigated to reveal the essence of heat transfer enhancement as well.

2. Physical model

The three-dimensional geometry of parallel flow and counter flow in double-layered microchannel heat sinks is shown in Fig. 2. They all have the same flow area to compare the effect of channel geometry on heat transfer. The channel geometries in bottom layer are both complex structure, i.e., microchannels with triangular cavities and ribs, which were presented by Zhai et al. [6]. The reason is that heat remove form bottom layer is higher than that form upper layer. To design good heat dissipation as well as low pressure drop in microchannel heat sinks, the upper layer channels are complex structure (the same as bottom layer channels) and rectangular structure, i.e., structure 1 and structure 2, respectively. Thus, the effect of channel geometries and flow manners on heat transfer performance is discussed in our paper, as shown in Table 1.

The whole length, width and height of microchannel heat sinks is 18 mm, 3 mm and 0.7 mm, respectively. Moreover, the length, width and height of single microchannel is 10 mm, 0.1 mm and 0.2 mm, respectively. Each layer consists of ten channels. More detail dimensions of complex channel are shown in Fig. 2.

3. Methodology

3.1. Numerical method

Three-dimensional solid-fluid conjugate model is select to simulate the flow and heat transfer in double-layered microchannel heat sinks. Thus, the mathematical model of stable, laminar flow and heat transfer is depicted as following.