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Characteristics of entropy generation and heat transfer in double-layered micro heat sinks with complex structure

Y.L. Zhai, G.D. Xia *, X.F. Liu, J. Wang

Key Laboratory of Enhanced Heat Transfer and Energy Conservation Ministry of Education, College of Environmental and Energy Engineering, Beijing University of Technology, Beijing 100124, China

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ABSTRACT

A new type of double-layered micro heat sink (DL-MCHS) with complex structure is designed and investigated numerically. Moreover, a model of entropy generation rate of DL-MCHSs is also derived from the first and second laws of thermodynamics. Results for the relationship of entropy generation rate between the first and second layer of DL-MCHSs, total entropy generation rate, the average temperature on the bottom wall, thermal resistance and pressure drop are investigated in detail, respectively. The results indicate that the effect of entropy generation rate of the first layer on total entropy generation rate is dominant. The thermal characteristic of DL-MCHSs with complex structure is better than that of all DL-MCHSs and single-layered micro heat sinks (SL-MCHSs) with simple structure under the same volumetric flow rate. However, DL-MCHSs only show better thermodynamic advantage and thermal performance than SL-MCHSs with complex structure when the volumetric flow rate larger than a certain value. It is not reasonable to use DL-MCHSs for cooling microelectronic equipments under small volumetric flow rate due to the larger irreversibility. Finally, the pressure drop of DL-MHCSs can be reduced by properly changing the channel height under various volumetric flow rates. Due to the less irreversibility and more uniform temperature distribution on the bottom wall, DL-MCHSs can effectively eliminate the internal thermal stresses in microelectronic equipments. Therefore, DL-MCHSs are an alternative method for the electronic cooling. Moreover, the thermodynamic analysis provides references for the actual application design.

1. Introduction

With the growing increment of integrated density and heat generation by the microelectronic equipment, the heat removal has become an important challenge for their thermal performance and lifespan. It is important to keep the peak temperature lower than the acceptable temperature levels [1–3]. The uniformity of temperature distribution is also helpful for the reliability and lifetime of microelectronic equipment. DL-MCHSs are an alternative method for cooling the microelectronics, due to its large heat transfer area to volume ratio and high-heat-flux removal ability compared to SL-MCHSs.

A DL-MCHS was firstly proposed by Vafai et al. [4], which was one atop the other with the coolant flow in the same or opposite direction in each layer. At the same time, the thermal performance with counter flow was studied numerically. They pointed out that both the temperature rise and pressure drop were substantially lower than that in SL-MCHSs. Following their works, a considerable effort has been devoted to the study of the characteristic of the flow and heat transfer in such micro heat sinks [5–12].

Wei et al. [5] performed experimental and numerical works for coolant cooling in a stacked micro heat sink, and then found both the thermal resistance and pressure drop to be generally lower than that in SL-MCHSs. Levac et al. [6] conducted a comparison of the performance of DL-MCHSs between parallel flow and counter flow, respectively. They found that the thermal resistance of parallel flow was lower than that of counter flow at low Reynolds number, whereas counter arrangement was found to be superior in terms of the uniformity of the bottom temperature. Xie et al. [7] investigated the characteristic of flow and heat transfer in DL-MCHS. Their results showed that DL-MCHS not only reduced the pressure drop but also had better thermal performance compared with SL-MCHS under the same pumping power. Wu et al. [8] numerically conducted DL-MCHS with current flow under different geometrical parameters and flow conditions. They found that the overall performance increased by adjusting the inlet velocity of upper channels to

* Corresponding author. Tel.: +86 1067392176; fax: +86 1067391983.
E-mail address: xgd@bjut.edu.cn (G.D. Xia).

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Nomenclature

c_p	specific heat capacity, kJ/(kg K)
h	specific enthalpy, kJ/kg
H_b	height of baseplate, mm
H_{ch}	height of channel, mm
H_t	height of cover plate, mm
L_{ch}	length of microchannel, mm
$\dot{m}$	mass flow rate, kg/kJ
$N_{s,a}$	augmentation entropy generation number
PP	pumping power, W
Δp	pressure drop, Pa
Q	heat input, W
q'	heat flux along the flow direction, W/m
q''	heat flux per area, W/m^2
R_{th}	Thermal resistance, K/W
$\dot{S}_{gen}$	entropy generation rate, W/K
T_b	average temperature of bottom wall, K
T_f	average temperature of fluid, K
T_{in}	inlet temperature, K
W_{ch}	weight of channel, mm
W_b	Pitch between channels, mm

Greek symbols

λ_f	thermal conductivity of fluid W/(m K)
λ_s	thermal conductivity of solid, W/(m K)
μ_f	dynamic viscosity, kg/(m s)

Subscripts

1,2	first and second layer
b	bottom
s	solid
f	fluid
in	inlet

be smaller. However, DL-MCHS need more pumping power than SL-MCHS under the same inlet velocity.

In order to improve the heat dissipation capacity of channels, constructal theory presented by Bejan [13] was applied into the design guidance of actual applications. Follow then, many researchers began to investigate the thermal performance of actual applications based on the constructal theory. A micro heat sink with bifurcations was numerically investigated by Xie et al. [14]. They pointed out that the proper design of the multistage bifurcation could improve the overall thermal performance. Pouzesh A et al. [15] studied several shapes of cavity in the trapezoidal solid to minimize the peak temperature based on the constructal theory. They found that Y-shaped cavities were the most reliable and effective. Hajmohammadi et al. [16,17] designed square-shaped fin and T–Y shaped assembly of fins using the constructal theory to remove heat from heat sources. Moreover, Li et al. [18] and zhang et al. [19] both studied the micro heat sinks with Y-shaped bifurcation plates and the micro heat sinks with multiple bifurcations based on the constructal theory, respectively.

In addition to the investigation of thermal performance of DL-MCHSs, recently Huang et al. [9–11], Lin et al. [12] and Leng et al. [20] conducted a series of optimized works of such heat sinks by using conjugate-gradient method.

DL-MCHSs with simple structure, i.e., rectangular cross-section microchannels, had been widely investigated by many authors. Zhai et al. [21] and Xia et al. [22] pointed out that the combined effect of cavities and ribs in microchannels caused better thermal performance when compared with rectangular microchannels, due to the growth of thermal boundary layer and the increase of flow turbulence. Hajmohammadi et al. [23] proposed some simple types of cavities intruded in the rectangular and trapezoidal body. The results showed the peak temperature in the heat generating body could be effectively reduced by these simple cavities.

Table 1 summarizes some important conclusions about DL-MCHSs. From Table 1, we can see that DL-MCHSs with simple structure (Rectangular structure) have been investigated extensively. However, DL-MCHSs with complex structure received relatively less attention. Sharma et al. [24] considered the performance of DL-MCHS with trapezoidal structure and compared it with DL-MCHS with simple structure, which showed superiorly in the aspects of thermal resistance and temperature variations. A DL-MCHS with wavy structure was proposed by Xie et al. [25], which showed that wavy micro heat sink had better thermal performance over the traditional micro heat sinks.

The above literature review showed that the authors all considered as DL-MCHSs having better thermal performance than

Table 1
Some important information about DL-MCHSs in literature.

Authors	Year	Type of MCHSs	Flow type	Results
Vafai et al. [4]	1999	Rectangular	Counter flow	• The concept of DL-MCHS was presented firstly • Both thermal resistance and pressure drop were lower
Wei et al. [5]	2007	Rectangular	Counter flow Parallel flow	• Temperature at the first-layer wall was more uniform • Both thermal resistance and pressure drop were lower
Levac et al. [6]	2011	Rectangular	Counter flow Parallel flow	• SL-MCHS was superior to DL-MCHS in terms of pumping power at the same flow rate
Xie et al. [7]	2013	Rectangular	Counter flow Parallel flow	• Both thermal resistance and pressure drop were lower • Parallel flow was better for heat dissipation at the low flow rate, while counter flow was better at the high flow rate
Wu et al. [8]	2014	Rectangular	Counter flow	• DL-MCHS could decrease thermal resistance, the maximum temperature and temperature rise on the base surface compared with SL-MCHS. • DL-MCHS needed more pumping power
Sharma et al. [24]	2013	Trapezoidal	Counter flow Parallel flow	• DL-MCHS with trapezoidal structure showed superiorly in the aspects of thermal resistance and temperature variations when compared with DL-MCHS with rectangular structure
Xie et al. [25]	2013	Wavy	Parallel flow	• DL-MHCS with wavy structure showed better performance over the traditional DL-MHCSs