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A comparative analysis of innovative microchannel heat sinks for electronic cooling[☆]

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ABSTRACT

In this work, a comparative analysis of innovative microchannel heat sinks such as two-layered and multi-layered microchannel heat sinks (MCHS), or thin films within flexible complex seals and cooling augmentation using microchannels with rotatable separating plates, is presented. A compilation of the numbers of layers, main characteristics, setups, advantages and disadvantages, thermal resistance, pumping power in double-layer (DL-MCHS) and multi-layer MCHS (ML-MCHS) is presented. In addition, the thermal resistance is analyzed in order to present a comparison between the single-layer MCHS (SL-MCHS) and multi-layer microchannels. The results of comparison indicates that double-layer and multi-layer MCHS have lower thermal resistance and require smaller pumping power and they resolve the high streamwise temperature rise problem of SL-MCHS.

1. Introduction

The heat removal issue has become increasingly important in electronics applications. In this work, innovative microchannels are investigated. Microchannels were first introduced by Tuckerman and Pease [1]. Microchannel heat sinks maximize the surface area, minimize the thermal resistance, and thus increase the heat transfer from the component into the surroundings while offering a compact cooling system.

The large majority of microchannels studies in the literature are based on single-layer microchannels. The disadvantage of SL-MCHS is the relatively high streamwise temperature rise which can have an adverse influence on the equipment. This high streamwise temperature rise is caused by heat released by the equipment and carried out by a relatively small amount of coolant, which results in a high streamwise temperature. Hence, the undesirable high temperature rise causes larger thermal stress, for example, in chips and electronic packages due to the coefficient of thermal expansion mismatch among different materials thus undermining device reliability. In addition, the adverse effects of many electrical parameters are caused by a sharp temperature rise. One way to reduce the undesired temperature rise in single-layered microchannels is to increase the pumping power, which can generate more noise and require bulkier packaging. This is certainly undesirable.

However, the two-layered microchannel, first established by Vafai and Zhu [2,4], as well as multi-layered microchannels also first established by Vafai and Zhu [3], reduce the undesired temperature gradient in the streamwise direction. The design concept is based on a two-fold microchannel structure, one atop another. For such an arrangement, streamwise temperature rise for the coolant and the substrate in each layer are remunerated through conduction between the two layers. Since the temperature gradient is much smaller than the SL-MCHS, the required pressure drop can be substantially smaller than SL-MCHS, which can require a significantly smaller pumping power.

Following the works of Vafai and Zhu [2–4], extensive investigations have been conducted regarding the two- and multi-layer microchannel heat sinks in order to optimize the configurations and improve the thermal performance for various applications. In this work, studies on ML-MCHS are investigated and synthesized. These are comprehensively summarized in Table 2. In this work, ML-MCHS main characteristics, icon diagram, advantages and disadvantages, thermal resistance and pumping power are characterized. Also the comparisons of thermal resistance and pumping power between the SL-MCHS and ML-MCHS are investigated.

2. Analysis

2.1. Thermal resistance

The overall thermal resistance, which is defined as

$$Q = \frac{\Delta T}{R_{\text{th}}} = qA_{\text{sub}} \tag{1}$$

$$R_{\text{th}} = \frac{\Delta T}{qA_{\text{sub}}} \tag{2}$$

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Nomenclature

A_{sub}	the area of the substrate (cm^2)
H_{ch}	channel height (μm)
H_{ba}	base thickness (μm)
L	microchannel length (μm)
W	microchannel width (μm)
W_{ch}	channel width (μm)
W_{fin}	fin width (μm)
N	channel number
ΔP	pressure drop (Pa)
q	applied heat flux (W/m^2)
Re	Reynolds number
h	heat transfer coefficient (W/m^{2}K)
R_{th}	overall thermal resistance (°C/W)
k	thermal conductivity (W/(m·K))
T_{in}	inlet temperature (°C)
u_{in}	inlet velocity (m/s)
Q	flow rate (ml/min)
l	truncation length of the top channel (μm)
x,y,z	coordinates (μm)
D	diameter (μm)
D_h	hydraulic diameter (μm)

Greek letters

α	aspect ratio ($=H_{ch}/W_{ch}$)
β	channel-to-fin width ratio
λ_l	dimensionless truncation length
Ω	pumping power (W/cm)

Subscripts

1	lower layer channel
2	upper layer channel
3	third layer
4	fourth layer
5	fifth layer
f	fluid phase
s	solid phase
np	nanopillar
rib	the horizontal base in the microchannel

$$R_{th} = \frac{T_J - T_{in}}{qA_{sub}} \tag{3}$$

where T_J is the junction temperature, T_{in} the inlet temperature of coolant, q the heat flux, Q the heat transfer and A_{sub} the base area of the heat sink.

In order to unify the overall thermal resistance, the unit overall thermal resistance is employed when comparing SL-MCHS and ML-MCHS cases.

$$R_{unit} = R_{th}A_{sub} \tag{4}$$

A wide range of pertinent SL-MCHS cases in the literature are selected and the unit overall thermal resistances are presented in Table 1 in order to establish a reasonable comparison. After arriving at the thermal resistance from the literature, the corresponding average thermal resistance for the SL-MCHS in the literature is calculated. The maximum and the minimum average values are used to find the average value. The final average unit overall thermal resistance for the SL-MCHS is obtained by calculating the average value among all the average values we have calculated.

The average value of the overall thermal resistance can be calculated simply by either:

$$R_{ave} = \frac{R_{max} + R_{min}}{2} \tag{5}$$

or

$$R_{ave} = \frac{R_1 + R_2 + \ldots + R_n}{n} \tag{6}$$

2.2. Pumping power

The pumping power is defined as

$$\Omega = Q_V \Delta p = u_{in} A_C \Delta p N \tag{7}$$

where Q_V is the volumetric flow rate, Δp the pressure drop, A_C the channel cross-sectional area and N is the number of channels.

In order to unify the pumping power, the unit length pumping power is calculated.

$$\Omega_{unit} = \frac{\Omega}{L} \tag{8}$$

where L is the total length of microchannel heat sinks.

The same way with thermal resistance is utilized in order to make a comparison.

The average value of the pumping power can be calculated simply by either:

$$\Omega_{ave} = \frac{\Omega_{max} + \Omega_{min}}{2} \tag{9}$$

or

$$\Omega_{ave} = \frac{\Omega_1 + \Omega_2 + \ldots + \Omega_n}{n} \tag{10}$$

3. Results and discussion

Table 1 shows the pertinent unit overall thermal resistance and pumping power in single-layer microchannel heat sinks in the literature and their average value.

Table 2 presents the synthesis of a wide range of the innovative design heat sink equipment for cooling applications. Also, included is an innovative design for the control of exit flow and thermal conditions using two-layered thin films by flexible complex seals and cooling augmentation using microchannels with rotatable separating plates, which were introduced by Khaled and Vafai [7,20]. Their main characteristics, icon diagram, advantages and disadvantages, thermal resistance and pumping power attributes are all illustrated.

The comparison between the SL-MCHS and ML-MCHS is presented in Table 3. In general, ML-MCHS improves the thermal performance of heat sinks by reducing the overall thermal resistance, and decreases the required pumping power. It should be noted that ML-MCHS reduces the thermal resistance, anywhere from 6.3% up to 97.9% and also the pumping power, anywhere from 26.1% up to 99.9%. It should be noticed that the few blanks in these three tables are because the values have not been provided in the corresponding references. In addition, regarding reference [17], nanopillars were added within the structure, resulting an increase in the thermal resistance. Also with respect to reference [21], due to different operating conditions, the pumping power increases.