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Parametric study on thermal and hydraulic characteristics of laminar flow in microchannel heat sink with fan-shaped ribs on sidewalls – Part 3: Performance evaluation

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A B S T R A C T

In order to comprehensively assess the performance of microchannel heat sink with fan-shaped ribs on sidewalls, this third part of a three-part study focuses on the relationship between thermal resistance and pumping power, and further the entropy generation rate and performance evaluation criteria, with water and silicon used as fluid and solid for the computational domain. The microchannel has the width of 0.1 mm and depth of 0.2 mm in the constant cross-section region. The geometric parameters include the width (0.05–0.4 mm), height (0.005–0.025 mm) and spacing (0.2–5 mm) of aligned or offset fan-shaped ribs. For deep insight into the basic mechanisms and properties of such heat sinks, the entropy generation rate due to heat transfer and fluid friction are separately studied. Results show that the fan-shaped ribs can lead to better comprehensive performance and the geometric parameters of fan-shaped ribs have a significant influence on the performance of such microchannel heat sinks. With the increase of the rib's height, the microchannel heat sinks with offset fan-shaped ribs gradually perform better than the ones with aligned fan-shaped ribs. With the decrease of the rib's spacing, the comprehensive performance firstly becomes better and then gradually deteriorates. For the microchannel heat sink with large rib's height and small rib's spacing, the increase of Reynolds number can lead to tremendously increase of entropy generation rate due to fluid friction, which can withdraw the decrease of entropy generation rate due to heat transfer and lead to the increase of total entropy generation rate, making the comprehensive performance worse than the smooth one. For Reynolds number ranging from 187 to 715 and studied geometric parameters, the best microchannel heat sink shows a 32% decrease in entropy generation rate and 1.33 in performance evaluation criteria, comparing with the smooth one.

1. Introduction

With the development of microelectromechanical devices, the microchannel heat sink has been successfully used for heat removal in a variety of devices, such as micropumps, microvalves, and microsensors. Further, the higher volumetric heat transfer densities require advanced manufacturing techniques and lead to more complex manifold designs. Recently, a significant amount of research work has been developed as innovative cooling techniques those have the potential to deliver high-heat flux rates for microelectronic applications [1]. Xu et al. [2,3] used the thermal boundary layer redeveloping concept to demonstrate the interrupted microchannel heat sink to improve the heat transfer performance. Chai et al. [4,5] took advantage of the interruption of boundary layer formation and establishment of secondary flow to develop the microchannel heat sinks with periodic expansion–constriction cross-sections. Cheng [6], Hong and Cheng [7] and Foong et al. [8] based on the enhanced mixing mechanism of cold and hot fluids to introduce the passive microstructures into the microchannels. Combining the advantages of interrupted microchannel and passive microstructures, Chai et al. [9] introduced the staggered rectangular ribs into the transverse microchambers for better heat transfer performance.

However, employing microchannel heat sink usually results in a higher pressure drop per unit length, although with higher heat transfer performance. Therefore, the application of microchannels to electronics cooling imposes severe design constraints on the system design. For a given heat dissipation rate, the flow rate, pressure drop, fluid temperature rise, and fluid inlet to surface

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Nomenclature

A	area, m^2
c_p	specific heat, $J{\cdot}kg^{-1}{\cdot}K^{-1}$
D_h	hydraulic diameter, m
$\bar{f}$	average friction factor
$\bar{f}_0$	average friction factor for the smooth microchannel
h	heat transfer coefficient, $W{\cdot}m^{-2}{\cdot}K^{-1}$
$\bar{h}$	average heat transfer coefficient, $W{\cdot}m^{-2}{\cdot}K^{-1}$
$\bar{h}_0$	average heat transfer coefficient for the smooth microchannel, $W{\cdot}m^{-2}{\cdot}K^{-1}$
H	height, m
k	thermal conductivity, $W{\cdot}m^{-1}{\cdot}K^{-1}$
L	length, m
$\dot{m}$	fluid mass flow rate, $kg{\cdot}s^{-1}$
Nu	Nusselt number
$\overline{Nu}$	average Nusselt number
$\overline{Nu}_0$	average Nusselt number for the smooth microchannel heat sink
p	pressure, Pa
Δp	pressure drop, Pa
PEC	performance evaluation criteria
P_p	pumping power, W
q	heat flux, $W{\cdot}m^{-2}$
Q	heat transfer rate, W
Re	Reynolds number
R_{th}	total thermal resistance, $K{\cdot}W^{-1}$
S_{gen}	entropy generation rate, $W{\cdot}K^{-1}$
$S_{gen,h}$	entropy generation rate due to heat transfer, $W{\cdot}K^{-1}$
$S_{gen,f}$	entropy generation rate due to fluid friction, $W{\cdot}K^{-1}$
T	temperature, K
$\bar{T}$	average temperature, K
u	velocity, $m{\cdot}s^{-1}$
$\bar{u}$	average velocity, $m{\cdot}s^{-1}$
$\dot{V}$	volume flow rate, $m^3{\cdot}s^{-1}$
x,y,z	three coordinates shown in Fig. 1, m

Greek letters

ρ	density, $kg{\cdot}m^{-3}$
μ	dynamic viscosity, Pa·s

Subscripts

a	ambient
c	cross section
in	inlet
f	fluid
out	outlet
pp	pumping power
r	rib
s	silicon

temperature difference requirements necessitate optimization of the channel geometry [1]. For the optimization design of microchannel heat sink, several experimental, numerical and theoretical studies on the optimization of microchannel heat sinks have been conducted. Tsai and Reiyu [10] and Liu and Garimella [11] established theoretical optimization models based on thermal resistance minimization for a given pumping power to predict microchannel heat sink performance. Singhal et al. [12], Kandlikar and Upadhye [13], Gosselin and Bejan [14], and Canhoto and Reis [15] carried out optimization methods based on the minimization of pumping power requirement for a given thermal resistance to evaluate the heat transfer performance. For further study the optimization of thermal and hydraulic resistances simultaneously with all relevant design parameters for microchannel heat sinks including geometric parameters, material properties and flow conditions, Xie et al. [16] used the relationship between the thermal resistance and the pumping power to evaluate the heat transfer enhancement performance of the microchannel heat sinks with internal vertical Y-shaped bifurcations. Famouri et al. [17] and Shi and Dong [18] applied optimization methods based on entropy generation minimization for the optimization of a variable-height shrouded fin array and microchannel with staggered arrays of pin fin structure, respectively. Promvonge et al. [19], Xia et al. [20,21], Chai et al. [9], and Zhang et al. [22] used the performance evaluation criteria to comprehensively access the heat transfer enhancement performance of microchannel heat sinks with passive microstructures.

In the first and second parts of this three-part study, three-dimensional numerical models have been carried out to examine the laminar flow and heat transfer characteristics in the microchannel heat sink with fan-shaped ribs on sidewalls. To study the effects of geometric parameters of fan-shaped ribs on thermal and hydraulic characteristics, three non-dimensional variables have been designed, respectively representing the width, height and spacing of aligned and offset fan-shaped ribs. In order to comprehensively assess the performance of such microchannel heat sink, this part of the study is to focus on the relationship between thermal resistance and pumping power, entropy generation rate and performance evaluation criteria for laminar flow in such microchannel heat sink with the purpose of optimum channel geometric configuration.

2. Model formulation and solution methodology

Fig. 1a illustrates schematic of the enhanced microchannel heat sink, which also used as the computational domain. In this design, the fan-shaped ribs are mounted on the two parallel sidewalls in tandem for both aligned and offset arrangements. The computational domain has the length of 10 mm, width of 0.25 mm, and height of 0.35 mm. The microchannel has the length of 10 mm and the depth of 0.2 mm, respectively. The width of the two parallel sidewalls for microchannel without ribs (W_c) is 0.1 mm. The geometric parameters of fan-shaped ribs studied in this paper are shown in Fig. 1b, including the width (W_r), the height (H_r), and the spacing (S_r). The ranges for these geometric parameters examined in this paper are 0.05–0.4 mm for W_r, 0.005–0.025 mm for H_r, and 0.2–5 mm for S_r. Three non-dimensional variables are designed to analyze their effects on thermal and hydraulic characteristics, including the ratio of the width of rib to the spacing (W_r/S_r), the ratio of the height of rib to the width of the two parallel sidewalls (H_r/W_c), and the ratio of the spacing of ribs to the width of the two parallel sidewalls (S_r/W_c), respectively.

The simulations are performed using the ANSYS FLUENT 12.0 software. The SIMPLEC algorithm is applied to solve the governing differential equations for the velocity, pressure and temperature fields in the microchannels. These governing equations are listed as follows:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_i}(\rho_f u_i u_j) = -\frac{\partial p}{\partial x_j} + \frac{\partial}{\partial x_i}\left[\mu_f\left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j}\right)\right] \tag{2}$$