International Communications in Heat and Mass Transfer 93 (2018) 41–47

Contents lists available at ScienceDirect

International Communications in Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ichmt

Flow and heat transfer characteristics in double-layered microchannel heat sinks with porous fins

Shuo-Lin Wang, Xian-Yang Li, Xiao-Dong Wang*, Gui Lu*

State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China
Research Center of Engineering Thermophysics, North China Electric Power University, Beijing 102206, China
Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education, North China Electric Power University, Beijing 102206, China

ARTICLE INFO

Keywords:
Microchannel heat sink
Double-layered
Porous fin
Pressure drop
Thermal resistance

ABSTRACT

A new double-layered microchannel heat sink design is proposed in this work. The new design adopts porous fins instead of solid fins. A three-dimensional solid-fluid conjugate model is employed to compare the overall thermal resistance and pumping power of the new and original designs at Reynolds number ranging 65–200. The results show that with the same Reynolds number, the new design yields 45.3–48.5% reduction in pumping power, while it also deteriorates heat transfer with 14.8–16.2% increase in thermal resistance. Due to the noticeable friction reduction effect, the inlet flow velocity of coolant in the new design can be increased significantly to enhance convective heat transfer. With the same pumping power, the new design reduces the thermal resistance by about 10% in a wide range of Reynolds numbers. The predicted reduction efficiency of the pumping power is in good agreement with the existing model, confirming that the friction reduction can be attributed to "slip effect" of coolant on the porous fin walls. The effects of channel number, channel aspect ratio, and width ratio of channel-to-pitch on cooling performance on the new design are also discussed. The results show that with a constant Reynolds number, there are an optimal channel number and an optimal width ratio of channel-to-pitch to achieve the lowest thermal resistance; however, cooling performance monotonously depends on the channel aspect ratio and a larger channel aspect ratio can always yield a lower thermal resistance.

1. Introduction

Microchannel heat sink proposed by Tuckerman and Pease [1] in 1981 shows high heat transfer coefficient, low coolant requirement, small size, and compact structure etc., which has been regarded as one of the most promising cooling technologies for microelectronic devices with heat fluxes as high as $100\,\mathrm{W\,cm^{-2}}$. In recent thirty years, many studies devoted their efforts to enhancing convective heat transfer in a single microchannel and improving cooling performance of entire microchannel heat sink.

The cooling performance of microchannel heat sinks was found to be closely associated to coolant, solid fin material, and heat sink geometric structure [2]. Microchannel heat sinks commonly adopt rectangular channel shape and parallel channel arrangement. Channel number, channel aspect ratio, and width ratio of channel-to-pitch are three important parameters affecting heat sink performance. Single-parameter analysis [3] and multi-parameter optimization [2] have been implemented to search for the optimal values of these three parameters. To improve cooling performance of microchannel heat sinks, triangle [4,5] and trapezoidal [4,5] channel shapes as well as serpentine channel arrangement [6] were also proposed. Recently, nanofluids were extensively employed to replace water as coolant of microchannel heat sinks [7–11]. These studies demonstrated that nanofluids-cooled microchannel heat sinks show better cooling performance than water-cooled ones, with only slightly increasing pressure drop when low nanoparticles volume fraction are employed. Furthermore, adopting wavy microchannels [12–17], inserting porous materials [18,19], or adding microribs in microchannels [20,21] were also employed to enhance the heat transfer coefficient in microchannels and improve the cooling performance of microchannel heat sinks. However, the heat transfer enhancement always accompanies the increased pressure drop or pumping power.

Uniform cooling is also required for microelectronic devices. However, coolant is delivered to a microchannel heat sink and flows unidirectionally from channel inlets to outlets, inevitably leading to a non-uniform cooling along the flow path. Large temperature gradient in microelectronic devices may produce a large thermal stress, which deteriorates device stability and reliability and reduces device lifetime. To improve cooling uniformity, a double-layered microchannel heat sink design was proposed by Vafai and Zhu [22]. In this design, coolant

* Corresponding authors at: State Key Laboratory of Alternate Electrical Power System with Renewable Energy Sources, North China Electric Power University, Beijing 102206, China.
E-mail addresses: wangxd99@gmail.com (X.-D. Wang), lugui02@gmail.com (G. Lu).

https://doi.org/10.1016/j.icheatmasstransfer.2018.03.003

flows in the opposite direction in the top and bottom microchannel layers. Numerical predictions [23–26] and experimental tests [27,28] showed that the counter current flow arrangement of coolant remarkably decreases the temperature gradient along the flow path, as compared with single-layered microchannel heat sinks. Furthermore, the pressure drop for double-layered microchannel heat sinks is also lower than that of single-layered heat sinks.

It should be noted that in most of previous works, the heat transfer enhancement in microchannel heat sinks is commonly obtained at the cost of high pumping power. However, microchannel heat sinks are typically working with miniature pumps with limited pumping power capacities, and hence reducing pumping power becomes an important and challenging task. Recently, a new design of single-layered microchannel heat sink was proposed [29], where solid fins were replaced by porous ones. This design was found to have substantially lower pressure drop (about 45% reduction at $Re = 282$) than the conventional design with solid fins. The overall thermal resistance of the heat sink increases only by 4.74% at the same *Re*.

In this work, the porous fins design is incorporated into double-layered microchannel heat sinks (referred to as combined design. A numerical model based on the Forchheimer-Brinkman-Darcy equation is employed to investigate the flow and heat transfer characteristics of the combined design. Pressure drop and overall thermal resistance for the combined design are compared with the original double-layered microchannel heat sinks (referred to as original design) at various Reynolds numbers to demonstrate the advantages of the combined design. Subsequently, pressure drop and overall thermal resistance are investigated for the combined design with various channel numbers, channel aspect ratios, and width ratios of channel-to-pitch when the dimension of the heat sink remains constant.

2. Double-layered microchannel heat sink with porous fins

The schematic of double-layered microchannel heat sink is illustrated in Fig. 1(a), which is composed of two layers of microchannels and has a dimension of $L_x \times L_y \times L_z$, and each layer has N channels and N fins. Based on periodicity of the geometry, only one unit is modeled as the computational domain, as shown in Fig. 1(b). The top layer and bottom layer have the same dimension with channel height H_c, channel width W_c, fin width W_f, and horizontal fin thickness δ_f. In the original design, the fins are made of high thermal conductivity materials such as silicon, copper, or aluminum; however, to reduce pressure drop or pumping power, porous fins are used to replace solid fins in the combined design. Water is employed as coolant, and porous copper is employed to fabricate fins. Their properties are shown in Table 1.

Table 1
Material properties for water coolant and porous copper fins.

Material	ρ/kg m^{-3}	c_p/J kg^{-1} K^{-1}	k/W m^{-1} K^{-1}	μ/kg m^{-1} s^{-1}
Water	997	4179	0.613	0.000855
Porous cooper	–	–	385	–

3. Numerical method

3.1. Governing equations

The bottom wall of a microchannel heat sink is commonly attached to the top of an electronic device. Heat is firstly transferred from the electronic device to the horizontal bottom fin and vertical fins by heat conduction, and then is adsorbed by coolant by convection. Hence a three-dimensional solid-fluid conjugate model is employed to predict the thermal and flow characteristics of the heat sink. The model adopts the following assumptions: (1) single, steady-state, impressible, and laminar flow in channels; (2) constant fluid and solid properties; (3) neglected gravitational forces, thermal contact resistance between the heat sink and electronic device, and heat losses to ambient; (4) homogeneous and isotropic porous fins, fully saturated with fluid; (5) local thermal equilibrium between the solid and liquid phases inside the porous fins.

The governing equations for the channel are written as follows [2].

$$\nabla\cdot\vec{V} = 0 \tag{1}$$

$$\rho_f(\vec{V}\cdot\nabla)\vec{V} = -\nabla p + \mu_f\nabla^2\vec{V} \tag{2}$$

$$\rho_f c_{p,f}\vec{V}\cdot\nabla T = k_f\nabla^2 T \tag{3}$$

For the porous vertical fins, Forchheimer-Brinkman-Darcy model is employed [29].

$$\nabla\cdot\vec{V} = 0 \tag{4}$$

$$\rho_f(\vec{V}\cdot\nabla)\vec{V} = -\nabla p + \mu_f\nabla^2\vec{V} - \left(\frac{\varepsilon\mu_f}{k_p} + \frac{\rho_f\varepsilon^2 C_F}{\sqrt{k_p}}|\vec{V}|\right)\vec{V} \tag{5}$$

$$\rho_f c_{p,f}(\varepsilon\vec{V}\cdot\nabla T) = k_{eff}\nabla^2 T \tag{6}$$

For the horizontal fins, only heat conduction takes place [2].

$$k_s\nabla^2 T = 0 \tag{7}$$

In the above equations, $\vec{V}$ is the velocity vector, T is the temperature, p is the pressure; ρ_f, μ_f, $c_{p,f}$, and k_f are the density, viscosity, constant-pressure specific heat, and thermal conductivity of coolant, k_s

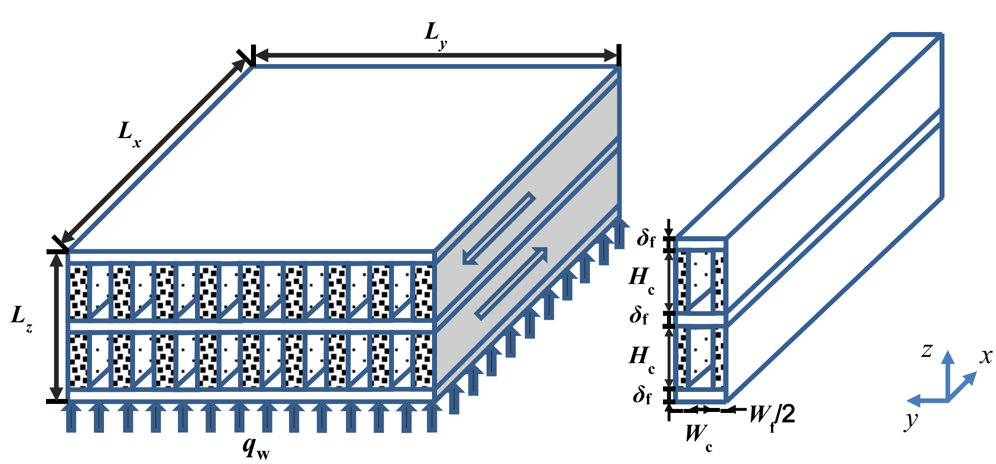

Fig. 1. Schematics of double-layer microchannel heat sink with porous fins: (a) heat sink and (b) computational unit.