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A new scheme for reducing pressure drop and thermal resistance simultaneously in microchannel heat sinks with wavy porous fins

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ABSTRACT

A new design of wavy microchannel heat sink with porous fins is proposed to reduce simultaneously pressure drop and thermal resistance. A three-dimensional solid-fluid conjugate model with considering heat transfer and flow in porous media is adopted to validate the effectiveness of the new design. The results show that the wavy microchannel heat sink with porous fins reduce simultaneously pressure drop and thermal resistance compared with conventional wavy microchannel heat sinks with solid fins. The marked pressure drop reduction in the wavy microchannel with porous fins comes from the combination of permeation effect and the slip effect of the coolant fluids. The improvement of heat transfer performance is attributed to the combinative effect of the enhanced coolant mixing by Dean vortices, the prolonged flow route by increasing equivalent channel length, and the forced permeation by jet-like impingement. The new concept is also examined for various microchannel heat sink designs with different wavy amplitude, wavelength, channel width and channel height, which indicates the wide range of applicability of the new microchannel concept.

1. Introduction

Microchannel heat sink has been shown to be a very effective way to remove high heat load in microelectronic devices, especially for those with heat dissipation levels exceeding the capacity of conventional air cooling systems [1–4]. A large heat transfer coefficient can be achieved by reducing channel hydraulic diameter. However, the decrease of hydraulic diameter will inevitably increase pressure drop, which need more pumping power to force the coolant through a greater number of small channels. In general, low thermal resistance is the desired effect while pressure drop penalty is how we pay for that effect. Due to the intrinsic conflict between heat transfer enhancement and pressure drop penalty, effective and innovative improvement is still needed for microchannel heat sinks to meet the ever-increasing cooling demands of microelectronic devices.

To enhance the heat transfer performance, a great number of efforts have been devoted to reducing thermal resistance of microchannel heat sink, such as surface modification [5,6]; increasing the heat transfer capacity of solid materials or coolant, e.g. high thermal conductivity solid materials [7] or nanofluids [8,9]; or novel designs, e.g., inserting solid ribs, porous blocks or baffles into the channel [10–15], or using wavy channels [16–20]. Among these designs, the outcome of lower thermal resistance usually accompanies with the penalty of high pressure drop, which is still an obstacle to the practical applications. The pressure drop can be reduced by using two-phase microchannel heat sinks [21–24], ultrahydrophobic surfaces [25], multi-layer designs [26–28] or porous fin design [29]. However, as expected, the thermal resistance is not reduced with these methods. The optimization method is a promising technique in microchannel heat sink designs, which has been widely used to ensure low thermal resistance and pressure drop of microchannel heat sinks [30–33]. Technically, an optimized design is only the tradeoff between the heat transfer and the pressure drop penalty, in which the lowest thermal resistance is always obtained with the restriction of an acceptable pressure drop. Reducing the thermal resistance simultaneously with low pressure drop penalty is still in its challenging research.

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In our previous studies, we proposed a novel concept of microchannel heat sink using porous fins rather than conventional solid fins [29]. The new design remarkably reduces pressure drop by 43.0–47.9%, while thermal resistance only increases by 4.1–4.9%. With such a superiority of pressure drop controlling, the porous fin microchannel heat sink can be further improved in the heat transfer performance, even though the reducing of thermal resistance might cost some pressure drop penalty. Therefore, we propose a new design of wavy microchannel heat sink with porous fins to reduce simultaneously pressure drop and thermal resistance in this work. A three-dimensional solid-fluid conjugate model with considering heat transfer and flow in porous media is adopted to validate the feasibility of the new design. The mechanisms on reduction of the pressure drop and thermal resistance are explained with flow and thermal details. In addition, a parametric analysis is performed to examine the application scope of the new concept microchannel heat sinks.

2. Methods

2.1. Wavy microchannel heat sink with porous fins

Fig. 1 show the schematic of the wavy microchannel heat sink with porous fins. The heat sink consists 50 channels and 50 ribs with rectangular cross-section and has a dimension of $L_x \times L_y \times L_z$ = 14 × 10 × 0.35 mm^3. Each channel has a height of H_c and a width of W_c. The thickness of bottom silicon plate is δ. Due to the symmetry, only a symmetric unit is selected as the computational domain, which is composed of one microchannel and two half-fins, as shown in Fig. 1(b). The wavy microchannel in this work is generated by two parallel wavy vertical fins. Fig. 1(c) shows a wavy channel with constant wavelength λ and constant amplitude A. The profile of each wavy unit can be represented by two circular arcs. The thickness of vertical fin is W_f, which is made of porous silicon with a porosity of ε, as shown in Fig. 1(d). The wavy microchannel heat sink with porous fins can be fabricated using standard micro-fabrication techniques as traditional wavy microchannel heat sinks, which is photo-lithography and deep reactive ion etching.

2.2. Numericalmodels

A three-dimensional solid-fluid conjugate heat transfer model is used to study the heat transfer and flow in the heat sink. Forchheimer-Brinkman-Darcy equation is used to describe the flow in porous fins. The flows are incompressible, laminar and steady-state flows. The thermal properties of solid and fluid are independent of temperatures. The gravitational force is neglected due to the small size. The heat sink is thermal insulation from ambient. The porous fins are homogeneous, isotropic and saturated with coolant, and in local thermal equilibrium with the coolant.

The mass, momentum, and energy equations of the coolant are as follows:

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

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

$$\rho_f c_p \vec{V} \cdot \nabla T = k_f \nabla^2 T \tag{3}$$

where $\vec{V}$, ρ, p, μ, and c_p are the velocity vector, density, pressure, dynamic viscosity, and specific heat of the coolant, respectively. T is the temperature.

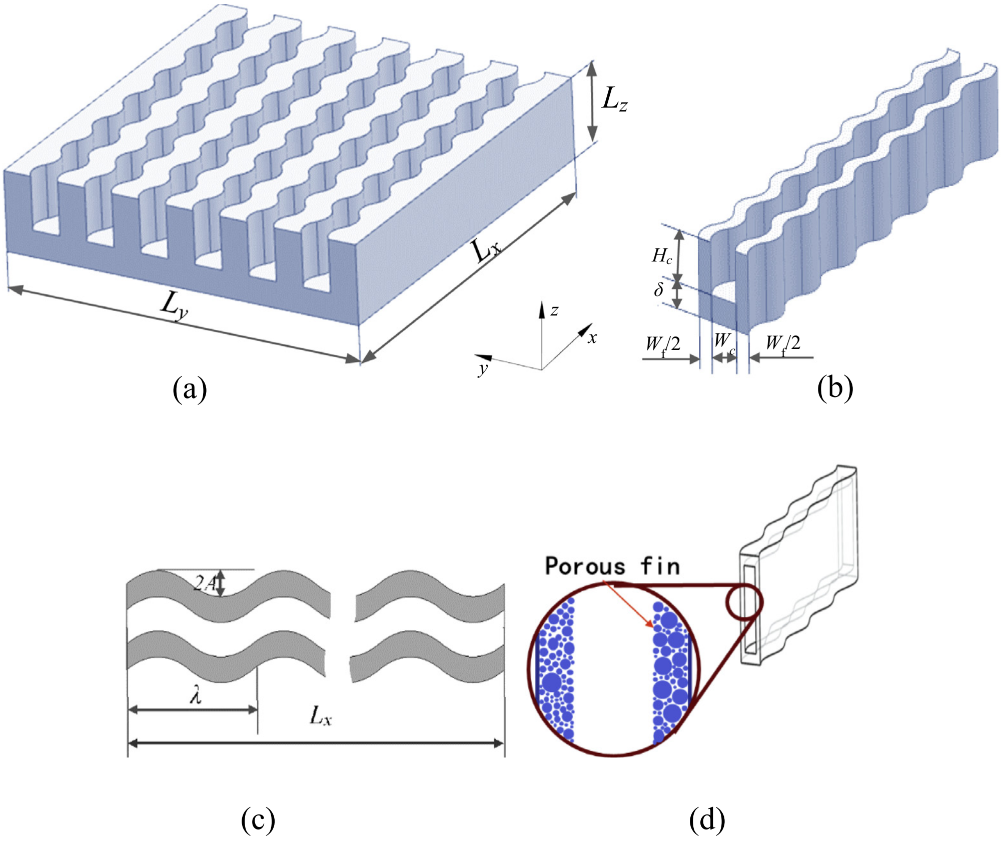

Fig. 1. The schematics of (a) wavy microchannel heat sink; (b) its periodic unit (simulation domain); (c) wavy length and wavy magnitude; (d) microchannel heat sink with porous fins.