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Heat transfer enhancement in microchannel heat sink by wavy channel with changing wavelength/amplitude

Lin Lin [a], Jun Zhao [a], Gui Lu [b, c], Xiao-Dong Wang [b, c, *], Wei-Mon Yan [d]

[a] School of Energy and Environmental Engineering, University of Science and Technology Beijing, Beijing, 100083, China
[b] Research Center of Engineering Thermophysics, North China Electric Power University, Beijing, 102206, China
[c] Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education, North China Electric Power University, Beijing, 102206, China
[d] Department of Energy and Refrigerating Air-Conditioning Engineering, National Taipei University of Technology, Taipei, 10608, Taiwan

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A B S T R A C T

An improved design of wavy microchannel heat sink with changing wavelength or/and amplitude along the flow direction is proposed. The thermal resistance R and the maximum bottom wall temperature difference $\Delta T_{b,max}$ for the new design are compared with those for the straight and the original wavy design under a constant pumping power. The results show that the new design performance is enhanced significantly with lower R and smaller $\Delta T_{b,max}$ when the wavelength of wavy units decreases or the amplitude increases. The enhancement becomes more remarkably when the absolute value of the wavelength difference $\Delta\lambda$ or amplitude difference ΔA between two adjacent wavy units increases. The performance can be further improved by simultaneously increasing the absolute values of $\Delta\lambda$ and ΔA. Moreover, as compared with the straight and the original wavy microchannel heat sink, the reductions in R and $\Delta T_{b,max}$ for the new design is found more significant for the heat sink with a smaller channel aspect ratio. The heat transfer enhancement is attributed to the formation of vortices in the channel cross sections caused by the curved walls, which promotes the coolant mixing and enhances the convective heat transfer between coolant and channel walls.

1. Introduction

Microchannels heat sink developed by Tuckerman and Pease [1] has become one of the most promising cooling approaches for microelectronic devices. It has attracted great attention in the recent two decades because of its outstanding advantages such as large heat transfer coefficient, low coolant requirements, small size, and high surface area-to-volume [2]. Many studies investigated the performance of microchannel heat sink theoretically [3,4], numerically [2,5–20], and experimentally [21–26]. These studies have demonstrated that microchannel heat sink could yield much better performance than conventional heat sinks. However, further improvement is still needed to meet the ever-increasing cooling demands of microelectronic devices.

Microchannel heat sink commonly employs straight channels with very poor fluid mixing because of the nearly straight coolant streamlines [13]. Meanwhile, the regular flow in these channels also inevitably leads to the heat transfer reduction along the coolant flow direction due to that the thermal boundary layer thickens [27]. To improve the heat sink performance, an idea of using wavy microchannels instead of straight ones was proposed [28]. The results showed that with the same cross-section, the wavy design achieves a much better heat transfer performance than that of the straight microchannels. It should be noted that wavy-wall designs were also employed in other heat transfer enhancement or mixing enhancement applications, such as large-scale heat exchangers [29], creeping flows in microfluidics [30], and natural convection heat transfer of nanofluids [31,32]. Following Sui et al.'s study, many works devoted their efforts to investigating and

* Corresponding author. Research Center of Engineering Thermophysics, North China Electric Power University, Beijing, 102206, China.
E-mail address: wangxd99@gmail.com (X.-D. Wang).

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optimizing the cooling performance of heat sink with wavy microchannels [33–48]. These studies showed the heat transfer enhancement can be explained by the thinning of the thermal and hydrodynamic boundary layers caused by centrifugal forces or the significantly improved convective fluid mixing due to secondary flow. Furthermore, these studies also indicated that geometrical parameters of wavy microchannels (amplitude and wavelength of wavy unit and shape of cross-section) [28,33,34,37,38,40,42–46,48], tortuous shape of wavy microchannels (zigzag, curvy, or step etc.) [35,42,46], and types of coolant (deionized water or nanofluids) [44,45,47] are the important factors affecting the cooling performance of wavy microchannel heat sink. It was found that the wavy microchannel heat sink with larger amplitudes and shorter wavelengths has better cooling performance [28,33,34,36,37,43,44,48], the zigzag channel yields always the better heat transfer performance than any other tortuous shape [35,42,46], the cooling performance can be enhanced significantly by nanofluids with low nanoparticle volume fractions as coolant [44,45,47]. To further improve the cooling performance, the double-layer wavy microchannel heat sink was developed by Xie et al. [40,41]. Their results showed that not only the heat transfer is enhanced remarkably, but also the pressure drop penalty is reduced, as compared with the single-layer wavy microchannel heat sink.

The wavy microchannels employed in the previous studies [33–48] are all uniform with constant amplitude and wavelength along the coolant flow direction. Sui et al. [28] presented that the relative waviness of microchannels defined as the ratio of amplitude to wavelength can be varied along the coolant flow direction for various practical applications. Moreover, the relative waviness can also be increased at high heat flux region for hot spot mitigation. It should be noted that in Sui et al.'s work, only two specific examples of wavy microchannels with changing waviness were discussed and the performances of the two new designs were compared with that of straight baseline channels but not with that of uniform wavy channels. Moreover, the comparisons were conducted at constant Reynolds number condition; thus, the heat transfer enhancement may come at the expense of increased pumping power. Accordingly, they employed two indicators to evaluate the performance improvement of the two new designs: the heat transfer enhancement and pressure-drop penalty defined as the average Nusselt number and frication factor of the new designs divided by that of straight baseline channels. In fact, constant pumping power for evaluating the cooling performance of microchannel heat sink is a more physically practical constraint condition because which implies that the power required driving the coolant through the heat sink is same.

Due to the reasons mentioned above, wavy microchannel heat sink with changing wavelength and/or amplitude along the flow direction are investigated at a fixed pumping power using a three-dimensional solid-fluid conjugate model in this work. The amplitude or wavelength of the new design varies along the flow direction in the form of arithmetic progression, and $\Delta\lambda$ (or ΔA) is defined as the wavelength (or amplitude) difference of two adjacent wavy units. To verify the effectiveness of the new design, its performance is compared with those of both the straight microchannel heat sink and the original wavy microchannel heat sink with a constant amplitude and wavelength under the same pumping power. To further enhance the cooling performance of the new design, the effects of $\Delta\lambda$ and ΔA are examined. Finally, the performance of the new design is studied for various channel dimensions including channel height and channel width.

2. Geometry of wavy microchannel heat sink

The microchannel heat sink (Fig. 1(a)) studied here is composed of 50 channels and 50 ribs with rectangular cross-section and has a bottom surface area of $L_x \times L_y = 14 \times 10\ \text{mm}^2$. Based on geometric symmetry, only one unit is modeled as the computational domain, as shown in Fig. 1(b), which includes one channel and two vertical half-fins. The channel height and width are denoted by H_c and W_c, respectively, while the vertical fin width is denoted by W_f. The thickness is δ for the bottom horizontal fin.

The wavy microchannel in the present work is generated by two parallel wavy vertical fins. Fig. 2(a) shows a wavy channel with a constant wavelength λ and amplitude A (original wavy channel design), which consists of seven wavy units. The profile of each wavy unit can be represented by two circular arcs. It should be noted that a circular arc can be determined uniquely by three given points. Therefore, once the values of λ and A are specified, the profiles of wavy units can be obtained. Fig. 2(b) illustrates a wavy channel with a changing amplitude or/and wavelength (new wavy channel design), which also consists of seven wavy units. Similar to the original design, the profile of each wavy unit for the new design is also represented by two circular arcs; however, the wavelength or/and amplitude for each wavy unit is changing along the flow direction in the form of arithmetic progression, i.e. λ_{i+1}-$\lambda_i = \Delta\lambda$ or/and A_{i+1}-$A_i = \Delta A$ ($i = 1, 2, 3, \ldots, 6$) remains constant, where λ_i and A_i denote the wavelength and amplitude of ith wavy unit.

In this work, three kinds of new wavy channel designs are adopted. In the first design, only the wavelength of wavy units varies, while the amplitude remains constant. In the second design, only the amplitude varies with a constant wavelength. In the third design, both the wavelength and the amplitude vary simultaneously. It should be noted that, to keep constant average wavelength or/and amplitude, in the new designs, the wavelength or/and amplitude of the fourth wavy unit is assumed to be the same as that in the original design.

3. Numerical model

3.1. Governing equations

A three-dimensional solid-fluid conjugate heat transfer model is employed to study the cooling performance of the heat sink. The following assumptions are adopted: (1) incompressible, laminar, and steady-state flow; (2) constant solid and fluid properties; neglected gravitational force; neglected heat losses between the ambient and the heat sink; neglected thermal contact resistance between the electronic device and the heat sink. According to the above assumptions, the governing equations for flow and heat transfer can be written as follows [2,18–20].

Continuity equation for the coolant:

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

Momentum equation for the coolant:

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

Energy equation for the coolant:

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

Energy equation for the solid fin: