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Thermal-hydraulic performance of interrupted microchannel heat sinks with different rib geometries in transverse microchambers

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ABSTRACT

The thermal-hydraulic performance of microchannel heat sinks with ribs in the interrupted transverse microchambers is studied using a three-dimensional conjugated heat transfer model and considering entrance effect, viscous heating and temperature-dependent thermophysical properties. Five different configurations of ribs and four lengths along the flow direction for every rib configuration are selected to analyze the effects of rib geometry on the thermal-hydraulic performance. The five rib configurations are rectangular, backward triangular, diamond, forward triangular and ellipsoidal, and the rib geometry parameters include expansion-constriction profile, ratio and length. The effects of rib geometry on thermal-hydraulic performance are firstly examined by the variations of friction factor and Nusselt number with Reynolds number, and corresponding correlations are proposed. Then, the conductive, convective and fluid capacitive thermal resistances are analyzed to obtain some insight into the basic heat transfer mechanism. Next, the entropy generation rates due to heat transfer and fluid friction are investigated for the analysis of the lost available work and irreversibility in the heat transfer process. Finally, the performance evaluation criteria is calculated to comprehensively assess the performance of such interrupted microchannel heat sinks with different rib geometry. For the studied operation parameters and rib geometries, the interrupted microchannel heat sinks with ribs in the transverse microchambers show a 4–31% decrease in the total thermal resistance, a 4–26% decrease in the total entropy generation rates, the maximum value 1.39 in performance evaluation criteria, compared with the straight microchannel heat sink.

1. Introduction

Since the pioneering work by Tuckerman and Pease [1] in the early 1980s, a great deal of investigations have concentrated on the fluid flow and heat transfer characteristics of microchannel heat sink. Due to its ability to dissipate a large amount of heat from a small area, the microchannel heat sink incorporating single-phase liquid flow has been successfully used in a variety of applications, such as the cooling of electronic devices, automotive heat exchangers, laser process equipment and aerospace technology, etc. However, with the advancements in micro and nano electronics technology, future requirement of heat flux dissipation rate is reaching 1 kW/cm^2 [2]. The traditional straight microchannel heat sink cooling system has become grossly inadequate and imposes limits on product design if no action is taken to develop more effective and innovative cooling methods. To meet such high heat flux removal rate using single-phase liquid, a significant amount of works have been conducted for innovative cooling techniques with the potential to deliver high-heat flux rates for microelectronic applications [3].

Xu et al. [4,5] used the thermal boundary layer redeveloping concept to demonstrate the interrupted microchannel heat sink which consisted of a set of separated zones adjoining shortened parallel microchannels and transverse microchambers. Chai et al. [3,6–9] 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 [10], Hong and Cheng [11] and Foong et al. [12] based on the enhanced mixing mechanism of cold and hot fluid to introduce the passive microstructures into the microchannels. Combining the advantages of interrupted microchannel and passive microstructures, Chai et al. [13,14] and Wong and Lee [15] introduced the staggered ribs into the transverse microchambers to improve the redeveloping thermal boundary layer. Combining the advantages of streamwise-periodic variations of cross-sectional area and passive microstructures, Xia et al. [16–18] and Ghani et al. [19,20] mounted the rectangular ribs into the microchannels with streamwise-periodically changed cross-sections for further heat transfer augmentation. Furthermore, Sidik et al. [21] reviewed the passive techniques for heat transfer augmentation in microchannel heat sink,

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Ghani et al. [22] comprehensively discussed the effect of channel design on the hydrothermal performance of microchannel heat sink, Dewan and Srivastava [23] reviewed the heat transfer enhancement through flow disruption in a microchannel, and Ghani et al. [24] comprehensively analyzed the effect of manifold zone parameters on hydrothermal performance of microchannel heat sink.

The combined heat transfer enhancement methods generally lead to a much better heat transfer performance, but the application of microchannel heat sink to electronics cooling imposes severe constraints on the system design. For a given heat dissipation rate, the flow rate, pressure drop, fluid temperature rise, and fluid inlet to surface temperature difference requirements necessitate optimization of the heat sink geometry [25]. For the optimal design of microchannel heat sink, several experimental, numerical and theoretical studies have been carried out. Tsai and Reiyu [26] and Liu and Garimella [27] established theoretical optimization models based on thermal resistance minimization for a given pumping power to predict microchannel heat sink performance. Singhal and Garimella [28,29], Gosselin and Bejan [30], and Canhoto and Reis [31] carried out optimization methods based on the minimization of pumping power requirement for a given thermal resistance to evaluate the heat transfer performance. Xie et al. [32] used the relationship between the thermal resistance and the pumping power to evaluate the heat transfer enhancement of the microchannel heat sinks with internal vertical Y-shaped bifurcations. Khan et al. [33], Famouri et al. [34], Shi and Dong [35], Zhai et al. [36], and Chai et al. [37] developed optimization methods based on entropy generation minimization, which was proposed by Bejan [38] for the first time, to 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. Promvonge et al. [39], Xia et al. [40,41], Chai et al. [13,37], and Zhang et al. [42] used the performance evaluation criteria (*PEC*) to comprehensively access the heat transfer performance of their proposed microchannel heat sinks.

For the interrupted microchannel heat sink with staggered ribs in the transverse microchambers, Chai et al. [14] has conducted three-dimensional numerical models to examine the local and average friction factor and Nusselt number of single-phase liquid, but they did not investigate the influence of rib geometry parameters and develop the pressure drop and heat transfer correlations, not carefully analyze the heat transfer process and discuss the entropy generation due to heat transfer and fluid friction. Further, as the study for optimal design of the rectangular ribs [13], the rib geometry parameters shows a significant influence on the thermal-hydraulic performance and thus the optimization design of heat sink. Therefore, in this paper, five different shape configurations of ribs are presented and four lengths along the flow direction for each rib configuration are designed to analyze the effect of rib geometry parameters, including expansion-constriction profile, ratio and length, on the thermal-hydraulic performance. The main work of this study is to carefully develop the correlations of pressure drop and heat transfer for such microchannel heat sink, elaborately demonstrate the thermal resistances of heat transfer process for deeper investigation, comprehensively discuss the entropy generation rate due to heat transfer and fluid friction and further the performance evaluation criteria for comprehensive evaluations with different operation conditions and rib geometries, with the primary objective to supply accurate data and useful information for the optimal geometry design of such heat sinks.

2. Model formulation and solution methodology

2.1. Geometry structure of microchannel

The interrupted microchannel heat sink with staggered rectangular ribs in the transverse microchambers studied by Chai et al. [13] is shown in Fig. 1a, which consists of 10 longitudinal microchannels with

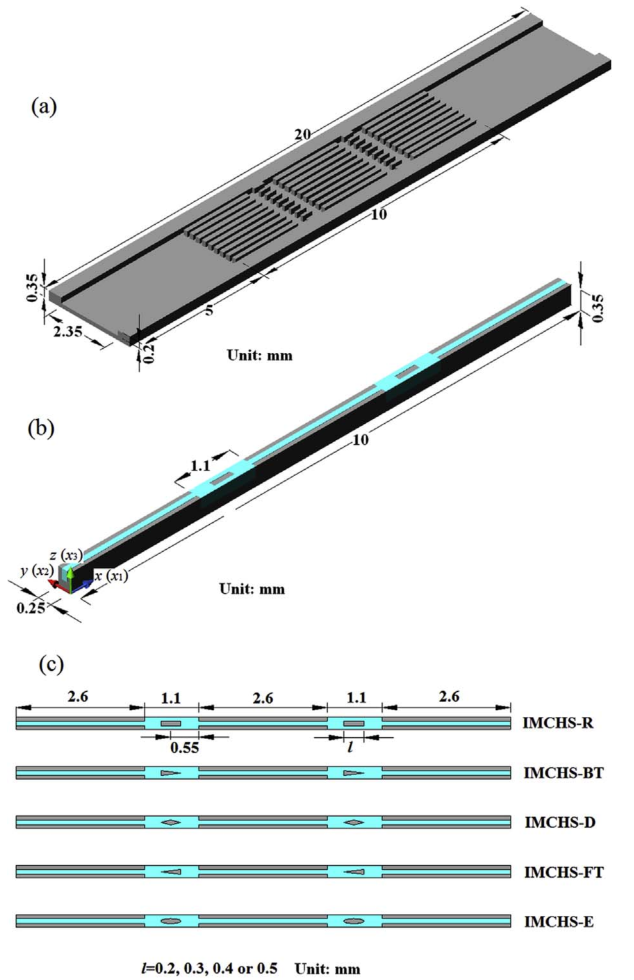

Fig. 1. Structure of interrupted microchannel heat sinks. (a) Interrupted microchannel heat sink, (b) computational domain and (c) rib geometry.

overall dimensions of 10 mm in length, 0.35 mm in height and 2.35 mm in width. To save the computation time and take advantage of symmetry, a control volume containing a single microchannel and surrounding solid along with the base is selected for developing the fluid flow and heat transfer model as shown in Fig. 1b. The length, width and height of the computational domain are 10 mm, 0.25 mm and 0.35 mm, respectively. The length, width and height for each microchannel region are 2.6 mm, 0.1 mm and 0.2 mm respectively. The length of the transverse microchamber is 1.1 mm and the staggered rib is located in its center. In order to study the effects of rib geometry on the thermal-hydraulic performance, five different rib configurations are considered, including rectangular, backward triangular, diamond, forward triangular and ellipsoidal, and four lengths along the flow direction are selected for every rib configuration as shown in Fig. 1c. The five interrupted microchannel heat sinks are respectively named for short as IMCHS-R, IMCHS-BT, IMCHS-D, IMCHS-FT and IMCHS-E. All the staggered ribs are 0.1 mm in *y*-direction, 0.2 mm in *z*-direction. The studied four rib lengths along the *x*-direction are 0.2, 0.3, 0.4 and 0.5 mm. To study the effects of expansion-constriction profile and ratio of rib geometry, the interrupted microchannel heat sinks are divided into two groups as shown in Fig. 2, one with different profiles (horizontal line, inclined line and ellipsoidal curve) but same expansion-constriction ratio (1), including IMCHS-R, IMCHS-D and IMCHS-E, and the other with different expansion-constriction ratios (0, 1 and ∞) but the same profile (inclined line), including IMCHS-BT, IMCHS-D and IMCHS-FT. Meanwhile, a straight microchannel heat sink without transverse microchamber (MCHS for short) and an interrupted