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Heat transfer and fluid flow characteristics of combined microchannel with cone-shaped micro pin fins

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ABSTRACT

This paper constructs a three-dimensional model to numerically investigate the heat transfer and fluid flow characteristics of combined microchannel with cone-shaped micro pin fins (MCPF) for inlet Re number ranging from 147 to 637. Firstly, the cases of micro pin fins located in the upstream (case1), middle (case2), downstream (case3) of microchannel and distributed throughout the microchannel (case4) are studied with fixed number of fins. Thereafter, the dimensionless parameters of relative fin diameter, relative space between the fins and relative height of the fin are studied to optimize the design. The variations of apparent friction factor $f_{app,ave}$ and average Nusselt number Nu_{ave} with inlet Re number have been conducted, and the thermal enhancement factor (η) has been adopted as evaluation criteria to determine the best comprehensive thermal-hydraulic performance of MCPF. The results show that the microchannel inserted cone-shaped micro pin fins improves the heat transfer accompanied with a higher pressure drop as compared with the smooth rectangular (Rec) microchannel. Microchannel with uniform fins distribution (case4) has the largest η and the bottom wall temperature is the lowest and well-distributed among all cases. When $Re < 500$, the overall thermal performance of case3 is better than case1 but when $Re > 500$, it displays a contrary tendency. The geometric configuration optimization of MCPF suggests that there is an optimum pin diameter, fin space and fin height that satisfy the demands of heat transfer and pressure drop.

1. Introduction

The rapid development of the industry had brought new challenges and opportunities for development of other disciplines, such as the rapid evolution in integrated circuits, the growing emergence of advanced energy and power, further improvement of the laser technology and so on. Common technical characteristics embodied in these fields from the point of view of heat transfer are high speed and frequency, high heat flux and micro/nano-scale. Thermal management has already become a key issue to limit the rapid development and reliable operation of electronic components. Thus, this led to a rising demand for more effective cooling method to ensure the reliable and efficient operation of microelectronic device.

Microchannel heat sink (MCHS) has been believed to be the most effective way to solve the cooling problem of electronic chip featured by high heat flux and small scale. Improving the heat removal rate of MCHS further has become a key issue in future development of high performance integrated circuits. Rectangular channel which is one of the most fundamental and effective structures of MCHS has been widely researched and applied in industry. Many investigators applied the analytical [1–2], numerical [3–4] and experimental methods [5–6] to explore the performance of this fundamental MCHS. Qu and Mudawar [7] carried out the experimental and numerical analysis to obtain the heat transfer characteristics and pressure drop of a single-phase MCHS. They demonstrated that the conventional mass and momentum equations, energy equations provided satisfactory simulations of the fluid flow and thermal performance of MCHS. Lee et al. [8] proposed the generalized correlations of local and average Nusselt number through the rectangular microchannel. The results showed that the prediction correlations matched well with the experimental and numerical results. Ryu et al. [9] conducted a three-dimensional analysis procedure to optimize the channel shape with the limitation of thermal resistance minimization. The results suggested that the channel width had a significant influence on performance of MCHS. Steinke and Kandlikar [10] extracted 5000 experimental date points to validate the appropriateness of traditional friction factor theory for microchannel with the range of Re and hydraulic diameter.

In recent years, as miniaturized and intensified processes of

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electronic components, traditional smooth and straight MCHSs cannot meet the demand of electronic chips' heat dissipation. Accordingly, various novel structural designs based on different heat transfer mechanism have been put forward, such as the extended surfaces, roughness surfaces which are able to increase the heat transfer area, disrupt the thermal boundary layer or induce secondary flow. Many researchers arranged micro-structures on the side-walls of smooth rectangular microchannel to ameliorate heat transfer performance. Chai et al. [11–13] numerically investigated the thermal and hydraulic performance of microchannel fabricated aligned or offset fan-shaped ribs on the side-walls. They also designed five different rib shapes on side-walls to compare the thermo-hydraulic performance of MCHS [14]. The shapes of rib included: rectangular, forward triangular, backward triangular, isosceles triangular, and semi-circular. The results revealed that the overall performance of microchannel with ribs is higher than smooth microchannel. The microchannel with forward triangular and semi-circular ribs exhibited the highest performance with $Re < 350$ and $Re > 400$, respectively. The heat transfer performance was enhanced in these microchannels due to the interruption and redevelopment of hydraulic/thermal boundary layer. Meanwhile, the ribs on the side-walls shifted the region of maximum velocity resulting in the local heat transfer improvement. However, the fluid velocity near the walls is still very low and the pressure drop penalty is very high. So, it requires an optimization procedure to the ribs construction in order to maintain lower pressure drop.

Introducing micro structures on bottom wall of channels is also widely used to enhance heat transfer due to the effect of shunt and acceleration of flow which increase the mixing between fluid layers near the wall and central core. Li et al. [15] inserted vertical Y-shaped bifurcations into microchannel and Xie et al. [16–17] designed multi-stage bifurcations at the entrance or exit region of the smooth microchannel. The results demonstrated that the thermal performance of microchannel combined bifurcations was better than smooth microchannel due to the generation of bifurcation flow. It might enhance the cooling performance resulting from the restarting of the boundary of layer. Micro pin fins surface is one of the most efficient means to improve the heat transfer of MCHS and the shape of pin fins, such as circular [18], cone-shaped, rectangular [19], hydrofoil [20], or square shape [21] have been studied adequately. What's more, some researchers inserted one or several micro pin fins aligned into the microchannel as the extended surface or vortex promoters to enhance the thermal performance. Shafeie et al. [22] used numerical method to compare the heat removal fluxes in pin-fined MCHSs and pin fin heat sinks. The results showed that the MCHSs with oblique pin-fins had better heat transfer performance and the higher depth of the microchannel in the studied case, the higher heat removal of the MCHSs. Adewumi et al. [23] made the minimum peak temperature and maximum thermal conductance as the objectives to optimize the geometric configuration of the microchannel inserted micro pin fins. The results indicated that microchannel inserted micro pin fins had less peak temperature and larger thermal conductance than microchannel without fins. Yadav [24] integrated the rectangular microchannel with cylindrical microfins as extended faces to enhance the thermal performance of the channel. The geometrical parameters were optimized by the univariate search method. Li et al. [25] and Ghani et al. [26] combined cavities arranged on sidewalls with ribs located at the channel center. They concluded that ribs at channel center were beneficial to promote the mainstream separation, increase the flow rate at cavities and enhance the impact effect of the fluid on the channel sidewalls.

It is obviously from above literature review, many studies have been done to optimize the geometric structure using ribs or micro structures with different geometries such as triangular, trapezoidal, circular and so on. The geometry strongly affects the heat transfer and flow characteristic of microchannel. Therefore, there is a need to explore new designs of micro pin fin that provides higher thermal performance in a lower pressure drop. Cone-shaped micro pin fin is an aerodynamic/hydrodynamic cross section shape connecting the semicircle with the triangle part. Since the friction factor of the streamlined pin fin (hydrofoil or cone-shaped) is lower than the other devices [19–20,27–28], cone-shaped micro pin fins are chosen to combine with smooth microchannel as a novel microchannel. Thus, present study aims to utilize the cone-shaped micro pin fins arranged on the central portion of the channel to enhance the performance of MCHS. The characteristics of fluid flow and heat transfer of combined microchannel and cone-shaped micro pin fin (MCPF) were investigated. In addition, the arrangement of micro pin fins has the significant influence on the overall performance of the microchannel. Therefore, the overall performance of fins located in the upstream (case1), middle (case2), downstream (case3) and the whole of channel uniformly (case4) compares with the smooth microchannel. Finally, the dimensionless geometrical parameters, relative fin diameter, relative space between the fins and relative fin height, are optimized with the evaluation criterion based on the thermal enhancement factor η.

2. Model description

Fig. 1(a) shows the schematic view of the whole MCHS with 30 longitudinal rectangular microchannels which is the reference channel for present study. The overall dimensions of MCHS are 10 mm in length (L), 10 mm in width (W) and 0.35 mm in height (H), respectively. The MCPF is a structural design which inserts the micro pin fins into the Rec microchannel in in-line arrangement and the geometric parameters are similar to the Rec microchannel. Due to the symmetry of each channel,

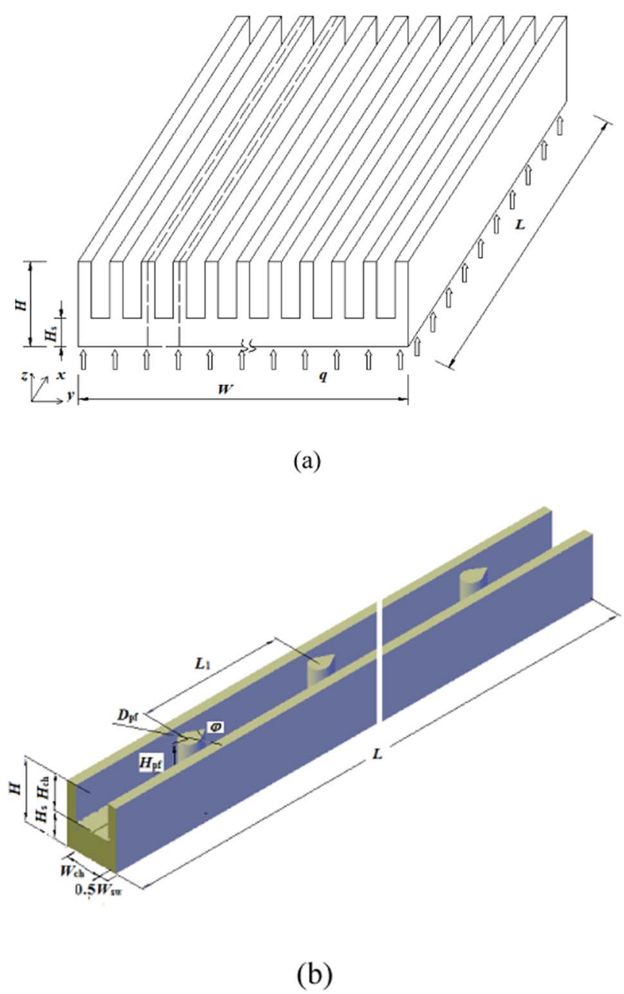

Fig. 1. The geometric parameters of (a) rectangular MCHS (b) a single MCPF.