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Heat transfer enhancement in microchannel heat sink using hybrid technique of ribs and secondary channels

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The flow and heat transfer characteristics of microchannel heat sink with secondary oblique channels in alternating direction and rectangular ribs (MC-SOCRR) are studied numerically for Reynolds number (*Re*) ranging from 100 to 500. The effects of secondary channels and ribs on the Nusselt number and friction factor are investigated. A comparative analysis has been conducted to the performance of the proposed design with related geometries such as microchannel with rectangular ribs (MC-RR) and microchannel with secondary oblique channels (MC-SOC). The results emphasized the superiority of overall performance of MC-SOCRR over both MC-RR and MC-SOC. The strategy which pursued by new design is the exploitation of larger flow area which provided by secondary channel to reduce pressure drop caused by ribs. Besides, the existence of the ribs in central portion of the channel is utilized to inject more flow through secondary channels for further enhancement in flow mixing. The effect of three geometrical parameters; relative width of secondary channel (λ) relative rib width (β) and angle of secondary channel (θ) on the convective heat transfer and pressure drop have been investigated. The MC-SOCRR with parameters; $\lambda = 0.666$, $\beta = 0.5$ and angle = 45° yields the best overall performance with $Pf = 1.98$ at $Re = 500$.

1. Introduction

Since the invention of the integrated circuits (IC), electronic industry has witnessed a tremendous transition towards miniaturization of electronic components. The accelerated growth in heat rates from these electronic components impose serious technical challenges in thermal management and control of electronics devices. A tiny size of silicon chip may consists of billions of transistors that works at high frequency. Besides, recent advances in laser technology has led to the use of components with high heat flux such as high power laser diode arrays and high energy mirror. This results in an ever increasing heat generation rate from these devices. For instance, the high power laser diode and high power electronic components (such as GaAs and Si based transistor amplifiers) dissipate heat fluxes of approximately 100–300 W/cm^2 [1]. Therefore, the traditional method of using air cooling becomes inadequate to handle such high heat flux concentrations. In the past two decades, many cooling techniques have been pursued to meet the requirements of high heat dissipation rate and maintaining a low junction temperature. These techniques include; micro-jet impingement, micro-heat pipe, micro-electro-hydrodynamic and microchannel heat sink. Among these techniques, microchannel heat sink MCHS appeared to be the most practical choice due to its favourable and attractive features such as light weight, compactness and higher heat transfer area to volume ratio [2]. Tuckerman and Pease [3] proposed the first concept of microchannel heat sink. They experimentally proved that the proposed MCHS can remove a heat flux of 7.9×10^5 w/m^2 with a maximum temperature difference of 71 °C between the substrate and the inlet water.

Since the invention of microchannel heat sink (MCHS), many researches have been devoted to study hydrothermal performance of the rectangular microchannel both numerically and experimen-

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tally. Peng [4] investigated experimentally the convective heat transfer and flow friction in MCHS with wide range of various hydraulic diameters of 0.133–0.367 mm. The results showed that both the flow and heat transfer in MCHS are significantly affected by the aspect ratio and the ratio of the hydraulic diameter to the centre-to-centre distance of the microchannel. Lee et al. [5] also conducted an experimental study of single-phase heat transfer through rectangular microchannel for a wide range of hydraulic diameters of (318–903)μm. The study is aimed to detect the correlations validity of conventional sized channel in the prediction of thermal behaviour in a rectangular microchannel. The results showed the possibility of employing conventional analysis approach in predicting heat transfer analysis in microchannel. Li et al. [6] confirmed numerically that heat transfer and fluid flow is significantly influenced by thermal properties of the liquid. Toh et al. [7] studied numerically the friction factor in MCHS. The results asserted that Poiseuille number decreases with the reduction in Reynolds number. The study attributed that to the reduction in water viscosity due to higher temperature at low Reynolds number.

Many other researches are focused on the effect of cross-sectional shape on hydrothermal performance of MCHS through studying various shapes such as; circular, triangular; trapezoidal [2,8–17]. Alfaryjat et al. [18] studied numerically the influence of three different cross-sectional channel shapes including; hexagonal, circular and rhombus. The results revealed that the hexagonal MCHS has achieved the highest heat transfer coefficient and pressure drop. Meanwhile, it is found that the rhombus cross-section MCHS showed the lowest friction factor and thermal resistance. Gunnasegaran et al. [19] also carried out a numerical simulation to study the effect of three shapes; rectangular, trapezoidal and triangle MCHS. The results showed that highest heat transfer enhancement is found in rectangular MCHS followed by trapezoidal and triangular MCHS.

Although high thermal performance can be achieved using MCHS, more improvement is still necessary to handle with the escalating thermal demands of electronic devices. The flow in conventional straight MCHS is predominantly within laminar flow regime due to its tiny scale. Accordingly, the ability of MCHS restricted to dissipate a specific limit of heat load. Therefore, researchers resorted to use heat transfer augmentation methods which are applied in conventional channels to increase the heat dissipation capability of MCHS. Tao et al. [20]suggested three strategies for the single-phase heat transfer enhancement. These strategies are; reducing the thermal boundary layer thickness, increasing flow disruptions and increasing velocity gradient near the heated surface. Also, Steinke and Kandlikar [21] and Kandlikar and Grande [22] proposed several techniques to promote heat transfer in microchannel such as; increase surface area and heat transfer coefficient using interrupted and staggered strip-fin design, increase local heat transfer coefficient by breaking boundary layer through periodic construction, incorporation of grooves and ridges, incorporation of mixing features to improve the mixing flow.

Ribs are one of the flow disruption techniques that are being used extensively to enhance heat transfer due to their ability to interrupt and redevelop thermal boundary layers and increase mixing through induced vortices and chaotic advection. However, the high-flow disturbances and blocking-flow effect which induced by ribs are increasing the pressure drop considerably. Therefore, the geometry and arrangement of ribs should be optimized to maximize the heat transfer and at the same time minimize the pressure drop.

Chai et al. [23–25] investigated numerically the effect of different geometric parameters on heat transfer and fluid flow in microchannel heat sink with fan-shaped ribs. Three geometric parameters have been studied; the rib height, width and spacing with two types of ribs arrangement; aligned and offset . The results showed that ribs with lower height and larger spacing produce better heat transfer performance. Besides, the microchannel with align ribs arrangement is thermally more efficient than offset arrangement. The Nusselt number has increased about 6–101% and 4–103% for align ribs arrangement and offset ribs respectively . At the same time, the study showed that friction factor has witnessed a significant increment of about 1.1–8.28 and 1.22–6.27 for align ribs arrangement and offset ribs arrangement respectively.

Chai et al. [26]investigated numerically the hydrothermal characteristics of microchannel heat sink with offset ribs on sidewalls. Five rib shapes had been chosen including; rectangular, forward triangular, backward triangular, isosceles triangular, and semi-circular. The study highlighted the role of ribs in heat transfer enhancement through the creation of secondary flow, vortices and boundary layer interruption. The results illustrated that microchannel with forward triangular offset ribs achieved the highest performance with Reynolds number less than 350. Meanwhile, the semi-circular ribs exhibited the highest performance with Reynolds number more than 400. The overall performance is ranged between (1.02–1.48) in comparison with simple microchannel.

To reduce the high pressure drop caused by ribs, many researchers have resorted to increase the flow area by combining grooves and ribs.

Xia et al. [27] computationally investigated the hydrothermal performance of MCHS with fan-shaped re-entrant cavities and internal ribs (FRCR). The effect of relative rib height had been studied for Reynolds number ranging from 150 to 600. The results showed that Nusselt number for FRCR increased about 1.3–3 times more than the rectangular microchannel, while the apparent friction factor increased about 6.5 times more. The study concluded that the moderate relative rib height of $e/Dh = 0.12$ at $Re = 592$, has achieved the highest thermal enhancement of (1.6).

Xie et al. [28] carried out a comparative study for the performance of four ribs with different shapes such as; rectangular, trapezoidal, triangular and circular with fan-shaped reentrant cavities. The results showed that at Reynolds number less than 300, the microchannel with fan-shaped reentrant cavities and trapezoidal ribs has showed a highest performance, while the circular ribs showed a best performance when Reynolds is more than 300.

Li et al. [29] performed numerical simulation of heat transfer and fluid flow in microchannel heat sink with triangular grooves arranged on side-walls and ribs in central portion of the channel. The results emphasized that the proposed design contributes in enhancing flow mixing through promoting the jetting, throttling and chaotic advection. In addition, it provides more flow area which reduces the pressure drop. The results indicated that the thermal enhancement factor for microchannel with relative rib width of (0.3) and relative cavity width of (2.24) achieved 1.619 at $Re = 500$.

Ghani et al. [30] proposed a new configuration of microchannel heat sink with sinusoidal cavities on the side-walls and ribs in the central portion of the channel. A numerical simulation was conducted to explore the hydrothermal characteristics of proposed design with a geometric optimization of three parameters; relative cavity amplitude relative rib width and relative rib length. The results showed that the proposed design significantly reduces pressure drop due to the enlargement in flow area which is provided by sinusoidal cavities. Also, the proposed design enhances flow mixing and chaotic advection which are attributed to the vortices formation in transverse direction of cavity. The results infer that the thermal performance factor for microchannel with relative cavity amplitude (0.15), relative rib width (0.3) and relative rib