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Thermal and hydrodynamic characteristics of divergent rectangular minichannel heat sinks

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ABSTRACT

For many years, miniaturizing the heat exchangers has led to the introduction of minichannel heat sinks (MCHSs) which offer a significant improvement in the heat transfer rate for cooling/heating applications. In this research, we aim to further improve the geometry of MCHSs by diverging the minichannels. Therefore, here a comparative study on hydrothermal performance of a parallel and divergent MCHSs with divergence angles of $\beta = 1.38°$ and $\beta = 2.06°$ is conducted. The volumetric flow rate of the working fluid is ranged from 100 to 600 cm^3/min under different heat flux intensities of 3.2×10^4, 4×10^4, and 4.8×10^4 W/m^2. To elucidate the thermal performance of divergent minichannels, the wall temperature distribution, average Nusselt number, pressure drop and the corresponding values of friction factor, thermal resistance of the coolant, and the cost of performance (COP) are evaluated at different experimental conditions. The results reveal that the divergent MCHSs have a clear advantage over the traditional parallel MCHSs for practical thermal applications; and they offer greater values of Nusselt number and COP along with lower pressure drop penalty, especially at higher flow rate of the working fluid.

1. Introduction

Today, energy conservation and management is of fundamental importance due to depleting energy resources. A passive heat transfer intensification technique has been the introduction of mini- and micro-channel heat exchangers [1]. Kandlikar and Grande [2] proposed a classification to characterize the micro/minichannels from the conventional channels. They mentioned that a typical minichannel heat sink (MCHS) is consisting of channels with the hydraulic diameter from 200 µm to 3 mm. In this regard, various researchers have investigated the thermal intensification in MCHSs. Dixit and Ghosh [3] conducted a review on the single-phase thermo-hydraulic investigations on the performance of micro/minichannels and clarified their practical applications and fabrication techniques used in this manner. Zhou et al. [4] performed an experimental study on the transient heat transfer of a MCHS under heat flux of 150–200 W/cm^2. They presented a detail description of wall and bulk fluid temperatures profiles along with the variation of pressure drop. Persoons et al. [5] investigated the impact of flow pulsation on the forced convection in a MCHS. Based on the pulsation amplitude, two operating regimes were characterized: (I) low pulsation amplitude where there was a slight reduction in the heat transfer, and (II) high pulsation amplitude where there was a significant improvement in heat transfer. Xie et al. [6,7] performed a numerical investigation on the laminar and turbulent heat transfer in a MCHS. They evaluated the variations of maximum allowable heat flux, temperature difference, and pressure drop at different inlet velocities, bottom thicknesses, channel wall thicknesses, and channel dimensions. They revealed that the best thermal performance can be achieved in a narrow and deep MCHS with thin wall thickness and thin bottom thickness.

A major effort for improving the performance of MCHSs is the implementation of nanofluids and/or phase change materials (PCMs) as the working fluid [8–10]. Nanofluids are widely used for various cooling and heating applications due to their superior thermal conductivity and heat capacity over the conventional fluids [11–18]. On the other hand, solid-liquid PCMs can absorb the heat through melting process and release it through solidifying, indicating their potential application as heat storage media [19]. Ho et al. [20] implemented Al_2O_3/water nanofluids in a MCHS. They showed that the heating and cooling performances of the

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Nomenclature

A_{base}	total base area of the heat sink (m^2)
AR	aspect ratio H_{ch}/W_{ch}
C_p	specific heat $\left(\frac{kJ}{kg}\cdot K\right)$
COP	coefficient of performance
D_h	hydraulic diameter
f	friction factor
FOM	figure of merit
H_c	heat sink bottom thickness (mm)
$\bar{h}_{itd}$	average heat transfer coefficient based on inlet temperature difference $(W/m^2\ K)$
I	current (A)
L_{ch}	minichannel length (mm)
$\overline{Nu}_{itd}$	average Nusselt number based on inlet temperature difference
P	pressure (Pa)
ΔP	differential pressure drop (Pa)
Pe	Peclet number
Pr	Prandtl number
$\dot{Q}$	volume flow rate (m^3/s)
q''	heat flux (W/m^2)
q_h	the heating power provided by the heater (W)
q_{eff}	the actual heat removal by the fluid (W)
R	thermal resistance (K/W)
Re	Reynolds number
Sb^*	modified inlet subcooling parameter $(T_m - T_{in})/\Delta T_{ref}$
Ste^*	Stefan number
T_{tc}	temperatures measured in the base block of the heat sink (K)
T_w	wall temperature (°C)
ΔT_{ref}	reference temperature difference (°C)
u_m	average flow velocity (m/s)
V	voltage (V)
W_{ch}	channel width (mm)
W_{rib}	fin width (mm)
β	divergence angle
θ_w	dimensionless wall temperature
ρ	density (kg/m^2)
ω	MEPCM concentration (%)
Ω	pumping power (W)

MCHS can respectively improve up to 22% and 62% by addition of 0.1–1.0 wt% nanoparticles. Moraveji et al. [21] investigated the employment of TiO_2 and SiC water-based nanofluids at different concentrations and inlet velocities. They revealed that the thermal performance of a minichannel is directly proportional to the nanoparticle content and Reynolds number. Sohel et al. [22] studied the performance of Al_2O_3 nanofluids in a MCHS and showed that the heat sink base temperature and the thermal resistance are remarkably decreased using nanofluids. Ho and Chen [23] employed the Al_2O_3 nanofluid in a MCHS with the length of 50 mm. They showed that not only the heat transfer would be increased in the presence of nanoparticles, but also the pumping power would be increased. Ho et al. [24] investigated the performance of water-based MEPCM suspensions in a MCHS and revealed that the heat transportation is enhanced compared to pure water, and this enhancement was more pronounced in low flow rates and low values of latent-sensible heat ratio. Nanoparticles and PCMs also can be simultaneously employed in MCHSs as a hybrid coolant [25,26]. Ho et al. [27] examined the thermal performance of MEPCM particles and Al_2O_3 nanoparticles suspension in a MCHS with a length of 50 mm, a depth and width of 1.5 and 1 mm, and with having a hydraulic diameter of 1.2 mm. They evaluated 2–10% concentration range for nanoparticles and PCM particles and showed that the average heat transfer coefficient could be enhanced up to 57%. In another study, Ho and Gao [28] studied the hydrothermal performance of the dispersion of MEPCM particles and Al_2O_3 nanoparticles in pure water and revealed that the dynamic viscosity and thermal conductivity of emulsions is increased by augmentation of nanoparticles concentration. The performance of the hybrid suspension was highly dependent on the temperature.

According to the open literature, miniaturizing heat exchangers has led to the significant improvement in the heat transfer rate for cooling and heating applications. However, apart from the implementation of nanofluids and/or PCM suspensions in MCHSs, the efficacy of the geometrical parameters of the minichannels on their performance has received much less attention. Jajja et al. [29] conducted a comparative study on the performance of five different MCHS configurations focusing on the effect of fin spacing. It was found that reducing the fin spacing results in lower thermal resistance and elevated overall heat transfer coefficient. Tullius et al. [30] studied the performance of the implementation of six different pin fin shapes including hexagon, diamond, ellipse, triangle, square, and circle in a rectangular MCHS to intensify heat transfer dissipation. The triangular fins were found to provide the highest Nusselt number improvement. However, the least pressure drop was achieved in the case of ellipse and circle fins due to their aerodynamic shapes. Xie et al. [31] designed a transversal wavy microchannel to investigate its flow and heat transfer behavior. They reported that a transversal wavy MCHS can significantly offer lower pressure drop penalty, especially higher wave amplitudes. Thus, a transversal wavy MCHS could outperform the traditional straight rectangular MCHSs. In another study, a sinusoidal wavy MCHS is employed by Khoshvaght-Aliabadi [32] to evaluate its cooling performance. Their results revealed that the heat transfer rate is directly proportional to the wave amplitude, while it is inversely proportional to the wave length. Later, a corrugated MCHS is investigated by Khoshvaght-Aliabadi and Sahamiyan [33] in the presence of Al_2O_3 nanofluid as the coolant. It was seen that this type of minichannels provides higher thermal performance with greater pressure drop penalty compared to the straight MCHSs. Moreover, the thermal resistance along with the base temperature was found to decrease by incrementing the wave amplitude and decrementing the wave length. In another study, Khoshvaght-Aliabadi and Nozan [34] focused on the effect of corrugation shape and showed that the trapezoidal, triangular, and sinusoidal corrugated MCHSs offer from higher to lower Nusselt numbers and pressure drop, respectively. According to the results, the maximum performance index was achieved for the sinusoidal corrugated MCHS. Fan et al. [35] introduced a novel cylindrical oblique-finned MCHS for fitting over cylindrical heat sources. This structure results in reinitialization of the hydrodynamic boundary layers at the leading edge of the fins, thereby elevated heat transfer rate due to thinner thermal boundary layer thicknesses. Accordingly, it was obtained that the thermal resistance can be reduced up to 59.1% and the Nusselt number can be increased up to 75.6% for the cylindrical oblique-cut fin MCHS. Later, Fan et al. [36] further evaluated the thermal performance of a cylindrical oblique fin MCHS with different oblique angles from 20° to 45°, Reynolds number from 200 to 900, and secondary channel gap from 1 mm to 5 mm. It was found that the boundary layer would be disrupted and secondary flow is increased by incrementing