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Numerical investigation into the thermo-fluid performance of wavy microchannels with superhydrophobic walls

Hamidreza Ermagan, Roohollah Rafee*

Faculty of Mechanical Engineering, Semnan University, Semnan, Iran

A R T I C L E I N F O

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A B S T R A C T

As an efficient cooling method, wavy microchannel heat sink (W-MCHS) with superhydrophobic walls is suggested as an alternative to a straight microchannel heat sink (S-MCHS) with conventional walls. Navier-Stokes and Energy equations with slip boundary conditions (velocity slip and temperature jump) are solved to study the hydraulic and thermal performances of the microchannels. It is observed that based on the "goodness factor" criterion, the overall performance of the new heat sink design is improved by 47.3%. In fact, the pressure drop reduction accompanying the use of superhydrophobic walls outweighs the thermal performance degradation due to the presence of trapped layers of air. It is also observed that with an increase in the waviness of the channel (either by an increase in the wave amplitude or a decrease in the wavelength), the pressure drop reduction by the use of superhydrophobic walls intensifies as the maximum velocity shifts from the centre of the channel towards the crest regions. This, in turn, increases the velocity gradient at the wall which excites the velocity slip and results in a better hydraulic performance. On the other hand, the thermal performance is deteriorated to a greater extent (compared to the hydraulic improvement) when the channel waviness increases, due to the elongated flow path and the related increase in the trapped layers of air. As a result, as long as the cooling performance of the heat sink with superhydrophobic walls is concerned, microchannels with lower waviness are desirable.

1. Introduction

Fluid flow and heat transfer in micro scale geometries have been the subject of extensive studies during the past three decades [1,2], making significant contribution to the development of Micro-Electro-Mechanical Systems (MEMS) [3], microfluidic devices [4] and bio-micro-systems [5]. Wavy microchannels, being no exception, have aroused researchers' interests ever since their capabilities of high heat flux removal [6,7], superior mixing index [8,9], and filter performance improvement [10] were highlighted. Thanks to the emergence of secondary flows due to the centrifugal forces, wavy microchannels show higher convective fluid mixing, and hence, higher heat transfer coefficient compared to straight microchannels [6]. Based on this premise, wavy microchannel heat sink (W-MCHS) is suggested as an alternative to the conventional straight MCHS (S-MCHS) initially proposed by Tuckerman and Pease [11].

Rush et al. [12] examined the fluid flow and heat transfer in wavy microchannels for Reynolds (Re) number below 1000. They observed that for a relatively low Re (~200), instabilities occur initially at the channel exit. These instabilities were found to emerge in the upstream regions when Re was increased. Sui et al. [6] numerically investigated liquid flow and thermal transport in a W-MCHS. In their study, Re number was kept below 800 in order to maintain flow in a steady-state regime. They observed that the changes in the patterns of Dean Vortices along the microchannels are accountable for the chaotic advection and the concomitant increase in heat transfer coefficient. In another work [13], they experimentally investigated thermal-hydraulic performance of a W-MCHS for Re numbers from 300 to 800. Wave amplitude of the wall was varied between 0, corresponding to an S-MCHS, up to 260 μm. They showed that numerical prediction based on classical steady state Navier-Stokes and energy equations with no-slip boundary conditions could accurately predict the obtained experimental data.

Although aforementioned studies seem to limit thermal improvement in wavy passages to high Re flows, some studies suggested considerable thermal enhancement at medium Re flows ($50 < Re < 150$). Gong et al. [14] numerically studied the liquid flow through wavy microchannels, to assess their cooling capability at medium Re regime. It was found that the effect of surface area increment due to wavy passage on thermal enhancement was insignificant and no formation of Dean Vortices were observed in their work. They concluded that the

* Corresponding author.
E-mail address: rafee@semnan.ac.ir (R. Rafee).

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Nomenclature

A	Wave amplitude (m)
C_p	specific heat (J kg^{-1} K^{-1})
D_h	hydraulic diameter (m)
f	average friction factor (-)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
H	channel height (m)
l_S	slip length (m)
L_x	length of the heat sink (m)
L_y	width of the heat sink (m)
L_z	height of the heat sink (m)
n	wall normal vector
Nu	average Nusselt number
p	pressure (Pa)
q	heat flux (W m^{-2})
Q	volumetric flow rate (m^3 s^{-1})
Re	Reynolds number
S	heat transfer surface (m^2)
T	temperature
u_{in}	inlet velocity (m s^{-1})
$\vec{V}$	velocity vector (m s^{-1})
W	channel width (m)
W_{fin}	fin width (m)

Greek symbols

δ	substrate thickness (m)
λ	wavelength (m)
μ	dynamic viscosity (kg m^{-1} s^{-1})
ξ_S	temperature jump coefficient (m)
ρ	density (kg m^{-3})
φ	goodness factor (-)

Subscript

f	fluid
m	mean
s	solid
w	wall

Superscript

*	dimensionless values

thinning of the thermal boundary layer is accountable for the thermal performance improvement of wavy microchannels. In another study [15], they showed that thermal performance of a W-MCHS is improved by 26% compared to an S-MCHS, due to the thinned thermal boundary layers at the trough regions of the wavy flow passage.

Many studies have achieved thermal performance enhancement in MCHSs, but with a pressure drop penalty. Shen et al. [16] used internal vertical bifurcation to enhance the overall thermal performance of an S-MCHS. They observed a slight pressure drop increment while the thermal resistance was effectively reduced. Xie et al. [17] performed a detailed study regarding the hydraulic and thermal performances of microchannels with internal Y-shaped bifurcation. They observed that this novel design improves the thermal performance of the heat sink compared to prior rectangular straight MCHSs. They also found that further thermal performance enhancement can be achieved by increasing the obstruction length or the angle between the two arms of the bifurcation. Zhang et al. [18] observed that when fluid flow at the entrance is divided into multiple branches by the use of bifurcations, the overall performance of the heat sink is improved considerably. This simply implies the fact that the thermal performance improvement outweighs the pressure drop increment, so that the overall cooling performance of the heat sink is improved. Porous metal foams (especially foams with high porosity) have shown to substantially reduce the thermal resistance of an MCHS with a pressure drop penalty [19]. Y-shaped bifurcation can also be employed in porous metal foams to enhance the overall performance of an S-MCHS. It is found that this enhancement is more obvious for higher values of flow Reynolds number [20]. A detailed study regarding the thermo-fluid performance of micro channels with rectangular-shaped obstruction is performed by Xie et al. [21]. It is found that for a fixed pumping power, the total thermal resistance of the heat sink is reduced when microchannels with flow obstructions are used instead of smooth microchannels, indicating an improvement in the overall performance of the heat sink. Thermal boundary layer re-development is shown to be accountable for this enhancement.

Wavy walls induce a large pressure drop along the microchannel, especially when liquid is used as the coolant. This issue not only harms the efficiency of the cooling systems by increasing the required pumping power, but also poses a serious threat to the reliability of devices because of the coolant leakage [22]. Recently, porous fins are proposed to be incorporated in a W-MCHS instead of conventional solid fins [23]. Porous fins are shown to enhance both the fluid flow and heat transfer characteristics of the heat sink, resulting in a considerable enhancement in the efficiency of a W-MCHS. Double-layered microchannels were initially introduced by Vafai and Zhu [24] to reduce the pumping power requirement for a prescribed cooling capacity. Two important parameters in the thermal design of a double-layered MCHS, i.e., the height ratio of the layers and the upper layer length, were also optimized in Ref. [25] to further enhance the overall performance of the heat sink. Shen et al. [26] proposed a new design of W-MCHS in which two layers of wavy microchannels were stacked in a staggered manner. This novel design causes the flow in the upper and lower layers of microchannels to swap. This, in turn, forces the boundary layer remixing and re-developing which increases the heat transfer coefficient. In order to reduce the excessive pressure drop in wavy microchannels, in the present study, superhydrophobic walls (hydrophobic walls with longitudinal micro/nano textures) are suggested to be incorporated instead of conventional walls (uncoated and smooth walls).

Superhydrophobic walls are made by designing micro/nano-ribs and cavities over surfaces which are coated with hydrophobic materials [27–29]. These micro/nano-textures are usually placed perpendicular [29,30] or parallel [28,29] to the flow direction. Due to the non-wetting properties of the superhydrophobic walls, liquid is unable to penetrate into the micro/nano-cavities, and these cavities are filled with air instead of water. As shown in Fig. 1, alternating no-slip and shear-free boundary conditions occurring in the water-solid and air-water interfaces, respectively, cause a velocity slip equal to the slip length times the local shear rate. Tretheway and Meinhart [31] showed that Navier's proposed boundary condition, i.e., $u_S = l_S\,(\partial u/\partial n)$, is accurate enough to predict the fluid flow in a hydrophobic microchannel. It was pointed out that a constant l_S of 1 μm can be considered for the tested hydrophobic wall and this parameter was found to be independent of shear rate for the examined flow rate. In fact, very high shear rates ($\sim 10^{11}$ s^{-1}) are to be applied on the wall surfaces to impose a nonlinear relation between the slip velocities and shear rates [32]. Due to the non-zero velocity of the fluid at the hydrophobic surface, fluid flow rate can be increased for a fixed pumping power, when slip length is in the order of the channel dimension [33]. Ou et al. [27] showed that little to no drag reduction is observed for water flows through a hydrophobic microchannel. They showed, however, that by the use of superhydrophobic surfaces, drag force reduction of 40% is possible. They also found that this drag reduction corresponds to a slip length of about