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Developing forced convection in converging–diverging microchannels

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ABSTRACT

In this paper, the effects of geometrical configuration on heat transfer performance and fluid flow of converging–diverging microchannels are studied numerically. Geometrical parameters are presented in nondimensionalized format, i.e., aspect ratio, S, waviness, λ, and expansion factor, γ. For five different aspect ratios and different levels of wall curvature, Nu and f are determined for three Re, i.e., 200, 400 and 600. Different mechanisms that affect the performance of the microchannel design are addressed and at each level of waviness, dominancy of each mechanism is discussed. Flow structures formed are studied and counter rotating vortices created in the trough region are found to have an adverse effect on heat transfer. At highly pronounced levels of wall curvature, chaotic advection is observed which results in higher heat transfer rates albeit with higher pressure penalties. Thus, converging–diverging design is introduced as a planar design with which chaotic advection may be achieved. A Performance Factor (PF) is proposed to capture heat transfer and pumping power characteristics of converging–diverging microchannels by comparing the wavy designs with their corresponding straight configurations. Based on the performance factor introduced, it is observed that the superiority of converging–diverging design shows itself at higher Re for which higher performance of up to 20% is observed.

1. Introduction

Thermal management of micro-electronics has emerged to be a critical issue for both operating performance and long term reliability of electronic devices. The recent report of ITRS [1] has pointed out a great concern about the thermal management of new generations of high performance chip packages as their dimensions go down continually. For instance, it is predicted that the needed heat removal of the new 14 nm chip generation is going to be greater than 100 W/cm^2. This heat removal demand can hardly be handled by air cooled heat sinks and new methods should be implemented for their thermal management. The proposed solution for addressing the required heat removal should also be able to answer hot spot issue, as there are situations in which the total power of the equipment is unchanged but the unwanted hot spots dictate the lower performance of the device.

Single and two phase liquid cooling of electronics, although not new [2], are among promising ways of future cooling technologies. Two phase cooling has the greater heat removal capacity. However, it certainly has greater difficulties to be implemented in actual systems. Thus, single phase heat removal remains an attractive technique for electronics cooling.

Straight minichannels and microchannels have been studied intensively by researchers both numerically and experimentally [3–9]. Due to the small dimensions of microchannels, it is widely accepted that the fluid flow in straight channels is mostly in the laminar regime and as a result, turbulent heat transfer is not viable. Thus, techniques which can further enhance mixing and thereby the heat transfer are of practical importance. Early works done by Sobey et al. [10–14] showed that furrowed channels can enhance mass transfer due to enhanced mixing. They further studied the flow in wavy walled channels and reported the flow structures they observed through two dimensional simulations and flow visualization. Nishimura et al. [15–21] studied flow characteristics in channels with wavy walls and specially the shapes we name them as converging–diverging. Nishimura's investigations were mainly on pulsed flow in corrugated channels which could maintain instabilities. Guzmann and Amon [22–24] did investigations on a 2D single furrowed converging–diverging channel with periodic boundary conditions at inlet and outlet. They showed that there may be a transition to Eulerian chaos for such shapes. Their study revealed the importance of further studies on furrowed channels as chaos was believed to enhance heat transfer as the result of better mixing.

Using wavy walled microchannels in heat sinks used for electronics cooling has gained attention recently as they have shown better heat transfer characteristics. Previous research done by our group [25] showed that wavy microchannels can significantly

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Nomenclature

A	wavy wall amplitude
a	average width of the channel
b	channel depth
C_p	specific heat capacity
D_h	hydraulic diameter of the averaged cross section
f	friction factor
h	heat transfer coefficient
k	thermal conductivity of the fluid
L	wavy wall wavelength
$\dot{m}$	mass flow rate
N	Number of furrows
Nu	Nusselt number
P	pressure
ΔP	pressure drop
PF	performance factor
PP	pumping power
Q	heat transfer rate
Re	Reynolds number
S	aspect ratio
T	temperature
U	mean velocity of the averaged cross section of the channel
u,v,w	velocity components
x,y,z	coordinates
Greek symbols	
γ	expansion factor
λ	waviness
μ	dynamic viscosity
ρ	density
Subscripts	
in	inlet
m	mean
max	maximum
out	outlet
w	wall

enhance heat transfer. Wavy microchannels are introduced as a planar shape which can make and maintain spatial chaos by spatial evolution of dean vortices. More recent works of Joshi et al. [26] and Mohammed et al. [27] also pointed out the superiority of wavy microchannels in enhancing heat transfer accompanied by acceptable pressure penalties.

Joshi et al. [26] studied the effect of geometrical parameters of wave amplitude, wavelength and aspect ratio for Re 50 to 150. They observed that the wavy walled microchannels are capable of enhancing heat transfer and that the wavy microchannels have a better performance than converging–diverging channels. However, it should be noted that the Re range in their study mostly contributes to laminar advection. In a recent study done by Zheng et al. [28] for zigzag shape channels with circular cross sections, effect of Re, Pr and geometry was studied and compared to straight microchannels, enhancements in heat transfer was observed due to the presence of chaotic advection.

In current study, by introducing non-dimensional geometrical parameters like waviness and expansion factor, a parametric study of the geometry effect is conducted to understand the relation between these non-dimensional parameters and the performance of the channel under laminar and chaotic advection regimes. Expansion factor which is introduced as a complementary to waviness has shown itself to be a critical parameter in the performance of the channel as two configurations with equal waviness but with different expansion factor can have very different behavior.

Special attention is needed to understand how the geometry is defined and what the equivalent straight microchannel of the converging–diverging configuration is. The mathematical model and proposed numerical solution are discussed and the validity of the results obtained is shown by performing grid independence studies and comparing the results with available literature. Effect of flow structure on the performance of the channel is discussed in terms of secondary flow formation and chaotic advection being present in the system. In addition to the geometrical study done, effects of Re are also discussed along with presentation of the results.

2. Mathematical modeling and numerical procedure

2.1. Geometry description

Fig. 1 shows the typical configuration of microchannel heat sink for back cooling of a chip. The sketch shown here represents the actual physical configuration of the problem. However, since we wish to compare the convective performance of the wavy walled microchannels, fluid domain under constant wall temperature boundary condition is studied numerically. Fig. 2 shows the computational domain from top view with the key dimensions specified. Cold fluid enters the microchannel with constant temperature of 300 K and as it gains heat from the side walls and bottom, it leaves the heat sink from the other side of the microchannel. Water as a Newtonian fluid with constant properties is considered as the coolant with the properties presented in Table 1.

Studying the effects of geometrical parameters on the performance of the microchannel is the main objective of this paper. From Fig. 2, there are five geometrical parameters:

- A: the wave amplitude of the wall.
- L: the wavelength of a single furrow.
- a: averaged width of the channel.
- b: channel depth.
- N: number of furrows for each channel.

These parameters can be represented by three salient dimensionless parameters as follows:

- Aspect Ratio, the ratio of width to depth of the channel, $S = a/b$.
- Waviness, the ratio of wall amplitude to its wavelength, $\lambda = A/L$.
- Expansion factor, the ratio of widest width of the channel to the narrowest width, $\gamma = (a + 2A)/(a - 2A)$.

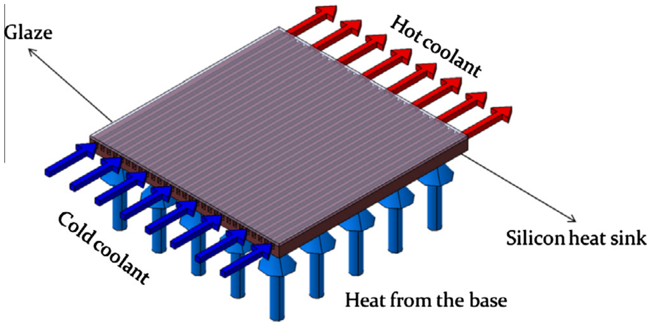

Fig. 1. Physical configuration of the problem.