International Journal of Heat and Mass Transfer 111 (2017) 484–494

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Single phase laminar flow and heat transfer characteristics of microgaps with longitudinal vortex generator array

Jian-Fei Zhang [a], Yogendra K. Joshi [b,*], Wen-Quan Tao [a]

[a] Key Laboratory of Thermo-Fluid Science and Engineering of MOE, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an 710049, China
[b] George W. Woodruff School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, GA 30332-0405, United States

ARTICLE INFO

Article history:
Received 15 January 2017
Received in revised form 12 March 2017
Accepted 12 March 2017

ABSTRACT

We study the integration of longitudinal vortex generators (LVGs) into microgaps for heat transfer augmentation via three-dimensional steady numerical simulations Firstly, the impacts of geometric parameters, including transverse spacing of LVG pairs, height of microgaps, and number of LVG pairs in the flow direction were considered. Then the heat transfer and flow resistance of LVG enhanced micro-gap were compared with smooth micro-gap. The results show that the flow resistance and heat transfer performance of LVGs enhanced microgaps decrease with increase in transverse spacing of LVGs. Microgaps with larger heights do not demonstrate a significant increase in heat transfer performance, but have much lower pressure drop. The microgap equipped with more LVG pairs has higher pressure drop and heat transfer coefficients. Finally, compared with the smooth microgap, the overall enhancement ratio of all studied LVGs enhanced microgaps increases with *Re*, and the overall enhancement ratios of specific LVGs enhanced microgap model is larger than one over the full range of *Re* being studied. The present study is intended to promote the development of new heat transfer enhancement technique in microgaps.

1. Introduction

With continued reduction in semiconductor feature size, power dissipation has become a limiting factor for higher-performance integrated circuits [1–4]. Three-dimensional (3D) stacked electronics present multiple advantages, including shorter interconnect lengths and the possibility of heterogeneous integration, such as logic and memory in a single device. However, the challenging thermal problem of significantly increased heat flux per chip footprint area must be overcome before 3D stacked electronics can be adopted for practical applications. To address the challenges in cooling of 3D stacked electronics, inter-tier microfluidic cooling, applying micro pin fin array in the microgap between tiers of 3D stack, has recently been employed. Such pin fin enhanced microgaps have been recently studied, including single-phase forced microfluidic cooling [5–9], two-phase microfluidic cooling [10–15], and configuration optimization of pin fins [16,17]. Besides the application in 3D ICs cooling, Li et al. studied micro-scale cooling for turbine blade surfaces by using pin-fin arrays [18,19].

Here we investigate LVGs as heat transfer enhancement features within microgaps. Jacobi and Shah [20], and Fiebig [21] have classified the flow disturbances used for heat transfer enhancement, in general, into transverse vortex generators (TVGs) and longitudinal vortex generators (LVGs). As pointed out by them, various pin-fin shapes can be classified as TVGs, which mainly generate transverse vortices-having their axes perpendicular to the flow direction. However, LVGs can generate longitudinal vortices with their axes in the flow direction. The longitudinal vortices persist for long distances in the flow direction, diffusing very slowly, thus exhibiting a promising potential for heat transfer enhancement. Since the 1990', the LVG has been introduced into large-scale heat transfer equipment, as a so called fourth generation heat transfer enhancement technique [22–29]. Some researchers also used LVGs to enhance the heat transfer in thermoelectric generator systems [30–32]. Recently, researchers have started to apply LVGs for enhancing the heat transfer in microchannels.

Liu et al. [33] carried out experiments on the flow and heat transfer in rectangular microchannels with and without LVGs. It was found that the LVGs can enhance the heat transfer in microchannel at the expense of a larger pressure drop. They also found that the laminar to turbulent transition is affected by the number, and the attack angle of LVGs. Empirical correlations for apparent friction factor and Nusselt number were developed. Extending the work of Liu et al. [33], Chen et al. [34] investigated the heat transfer in microchannels with different hydraulic diameters, and different heights of LVGs. They demonstrated that the overall heat transfer performance of some specific

* Corresponding author.
E-mail address: yogendra.joshi@me.gatech.edu (Y.K. Joshi).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.03.036
0017-9310/© 2017 Published by Elsevier Ltd.

Nomenclature

Latin symbols

A	area, m^2
A_c	cross sectional area of the inlet, m^2
A_{chip}	area of chip, m^2
A_p	projected area of the heated chip, m^2
b	width of the LVG, m
c_p	specific heat, $kJ/(kg \cdot K)$
D_h	hydraulic diameter, m
f	fanning friction factor
H_1	thickness of the chip, m
H_2	height of the microgap, m
h	heat transfer coefficient based on project area, $W \cdot (m^2 \cdot K)^{-1}$
h_{wet}	heat transfer coefficient based on the total wetted area, $W \cdot (m^2 \cdot K)^{-1}$
k	thermal conductivity, $W \cdot (m \cdot K)^{-1}$
L_1	length of the chip, m
L_2	stream-wise spacing of LVG pairs, m
l	length of the LVG, m
Nu	Nusselt number
Δp	pressure drop, Pa
p	static pressure, Pa
Q	total power applied on the heating surface, W
R	thermal resistance, K/W
Re	Reynolds number
ΔT	temperature differences, K
T	temperature, K
U_{in}	inlet velocity, $m \cdot s^{-1}$
u	velocity, $m \cdot s^{-1}$;
W_1	width of the chip, m
W_2	spacing between two LVG in transvers direction, m
W_3	spacing between two LVG pairs in transvers direction, m

Greek symbols

β	attack angle of LVG
η_{total}	overall fin efficiency of LVG array
μ	dynamic viscosity, Pa·s
ρ	density, $kg \cdot m^{-3}$

Subscripts

avg	average
cond	conduction
conv	convection
f	fluid
s	surface
smooth	smooth microgap

microchannels with LVGs was better than the corresponding smooth microchannel.

Ebrahimi et al. [35] conducted numerical analysis on the heat transfer of single phase laminar flow in rectangular microchannels equipped with two pairs of LVGs. They considered the influence of attack angle of the LVGs on the heat transfer performance. The results showed that the *Nu* and the friction factor for microchannels with LVGs were increased by 2–25% and 4–30% respectively. Ebrahimi et al. [36] also numerically studied the heat transfer for nanofluids (water-Al_2O_3 and water-CuO) in a rectangular microchannel with six pairs of LVGs. It was found that heat transfer could be enhanced greatly, compared to pure water. By using the same geometric model as in [36], Sabaghan et al. [37] performed numerical simulations of the flow and heat transfer of TiO_2-based nanofluids, and found heat transfer augmentation by using LVGs.

To the author's knowledge, there are only limited studies on the heat transfer enhancement in microchannels using LVGs. In these studies, only few LVGs (up to six pairs) were used in a single microchannel, with no studies focusing on microgaps ($H_2/W_1 \ll 1$ compared with microchannel, where H_2 is the height and W_1 the width of the flow passage). Also, a constant-temperature boundary condition was adopted by most of the microchannel studies [33–35]. A constant wall heat flux boundary condition is more in line with many electronic cooling applications. As another heat transfer surface modification approach, Wei et al. [38] applied dimples on the surface of micro-channels, which also showed heat transfer augmentation. However, the dimple array configuration does not allow electrical connectivity between the tiers of 3D stacked chips. Therefore, in this paper, we propose incorporatings LVGs into microgaps, and investigate the impact of LVGs arrays (up to around one thousand LVGs) on the heat transfer enhancement within microgaps with a constant wall heat flux boundary condition. We numerically study the single phase laminar flow and heat transfer, and discuss the impact of different geometric parameters on the heat transfer performance. The heat transfer performance of LVGs enhanced microgaps is compared with that of smooth microgap.

2. Geometric configurations and parameters

Fig. 1 indicates the arrangement of LVG array, and the definition of dimensions of the heated chip and LVGs. The size of the chip is 1 cm × 1 cm, the length of the LVG, *l*, is 200 μm, the width of the LVG, *b*, is 50 μm, and the attack angle (β) of the LVG is 45°. The thickness of the chip, H_1, is 100 μm in this study. More details about the geometric parameters of the different configurations are shown in Table 1.

3. Computational model and numerical method

Figs. 2 and 3 demonstrate the computational domain and boundary conditions. There is no gap between the tip of LVG and the top wall of the microgap. The inlet block is used to represent the flow development zone and the outlet block is used to prevent reverse flow at the outlet surface. Symmetric boundary conditions are applied between the LVGs to reduce the computational domain and computational cost. A uniform heat flux, 100 W/cm^2, is applied under the chip. Non-slip boundary condition is applied on all solid surfaces within the computational domain. Heat conduction within LVGs and the chip is considered by using coupled heat transfer module in ANSYS FLUENT [39].

The material of LVGs and chip is Si. Deionized-water (DI-water) is used as the coolant with the inlet temperature being 25 °C. The temperature-dependent thermo-physical properties for Si and DI-water are adopted in the calculation (Table 2) [35]. The deionized-water flow is assumed to be incompressible. The range of inlet velocity is determined based on the critical Reynolds number suggested by Liu et al. [33], to make sure all the computations are in the laminar region.

3.1. Numerical method

ANSYS FLUENT 15.0 is used to calculate the flow and heat transfer in the computational model. The QUICK scheme is used to