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A study on fluid flow and heat transfer in rectangular microchannels with various longitudinal vortex generators

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ABSTRACT

Based on our previous study, experiments were conducted to explore frictional pressure drop and heat transfer performance of de-ionized water flowing through rectangular microchannels having longitudinal vortex generators (LVGs). The experimental investigation was conducted under three-sided constant wall temperature boundary condition for the Reynolds numbers ranging from 350 to 1500 for LVGs with different number of pairs and dimensions. The aspect ratios of rectangular microchannels were 0.25 and 0.0667, and the corresponding hydraulic diameters were 160 μm and 187.5 μm, respectively. The heights of associated LVGs were 1/4*H*, 3/4*H* and *H*, respectively, where *H* was the height of microchannel. It was found that heat transfer performance was enhanced by 12.3–73.8% and 3.4–45.4% for microchannels with aspect ratios of 0.0667 and 0.25, respectively, while the pressure losses were increased by 40.3–158.6% and 6.5–47.7%, respectively; and the overall heat transfer performances of some specific microchannels were more than 1 in our study. With the help of LVGs, the critical Reynolds numbers were lower than 1000, which were smaller than the generally accepted value of 2300 for regular channel flow.

1. Introduction

Nowadays, owing to the rapid progress in passive heat transfer enhancement methods as well as Micro-Electro-Mechanical-System (MEMS) which continue to produce increasingly larger density in power and stricter limit in temperature, increasing demands have been generated for the applied researches in micro-scale thermal systems. Consequently, microchannels with LVGs as flow-disturbing elements were considered to be an efficient means to dissipate large amount of heat flux within a relatively small area. Therefore, it is necessary to have an in-depth understanding of the fundamental mechanism involved in heat transfer and flow behaviors of fluid flowing in such microchannels, even though the thermo-fluidic characteristics of micro-scale thermal systems often deviate significantly from those of macro-scale.

Many efforts have been done for the research of thermal and frictional characteristics in rectangular microchannles with different materials chosen as substrates in which microchannels were etched and various liquids or gases were used as working fluids. Tuckerman and Pease [1], in their pioneering work, demonstrated that rectangular microchannels had substantially high performance in heat transfer. Thereafter, the field related to microchannels had raised extensive concerns for numerous researchers to conduct relevant investigations. Peng et al. [2] performed an experimental study on flow characteristics using water as working fluid in rectangular microchannels with hydraulic diameters varying from 133 to 367 μm and aspect ratios ranging from 0.333 to 1. It was observed that the flow frictional behaviors obtained from their experimental results deviated from those obtained from conventional correlations for both the laminar and turbulent regimes. Wang and Peng [3] experimentally investigated the single-phase forced convection of water or methanol flowing through rectangular microchannels. Their experimental results indicated that the onset of fully developed turbulent flow was occurred at the Reynolds numbers ranging from 1000 to 1500, and the experimental data were in good agreement with the results predicted by the modified Dittus–Boelter correlation. Peng and Peterson [4] found that heat transfer performances were strongly influenced by the liquid temperature, velocity, and microchannel size; however, these performances were not solely determined by the Reynolds

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Nomenclature

A	area (m^2)
b	width of vortex generator (m)
C_p	specific heat (J/kg K)
D_h	hydraulic diameter (m)
f	Fanning friction factor
h	heat transfer coefficient (W/m^2 K)
h_v	height of vortex generator (m)
H	height of microchannel (m)
K	loss coefficient
l	length of vortex generator (m)
L	length of microchannel (m)
$\dot{m}$	mass flow rate (g/min)
Nu	Nusselt number
P	wetted perimeter (m)
ΔP	pressure drop (Pa)
Po	Poiseuille number
R	surface roughness (μm)
Re	Reynolds number
T	temperature (K)
u	velocity (m/s)
W	width of microchannel (m)
x	length in the streamwise direction (m)

Greek symbols

α_c	channel aspect ratio
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)
φ_f	relative ratio of Fanning friction factor between microchannel with LVGs and smooth microchannel
φ_{Nu}	relative ratio of Nusselt number between microchannel with LVGs and smooth microchannel

Subscripts

90	90° bend
1, 2, 3, 4	number of thermocouples
app	apparent
c	contraction
ch	channel
co	corrected property
cp	constant property
e	expansion
h	hydrodynamically developing region
i	inlet
m	arithmetic mean
o	outlet
s	sump
t	heat
w	bottom wall of test chip

numbers for both transition and laminar flow regimes. Popescu et al. [5] studied the heat transfer performance under the laminar flow condition of very shallow channels, which were 10 mm wide and 128–521 μm deep. Good agreement was found between their experimental results and conventional predictions. Qu et al. [6] and Wu et al. [7] demonstrated that convectional N–S and energy equations were still valid in predicting the heat transfer characteristics of microchannel heat sinks studied by them. Shen et al. [8] presented experimental analysis of convective heat transfer in rough copper heat sink, and their results showed that the average Nu number increased with increasing Re number and Pr number. The conclusion was in contradiction with that obtained from Tso and Mahulikar [9,10]. In addition, Shen et al. found that the surface roughness had a substantial effect on the laminar flow in microchannels.

On the other hand, the extended surfaces such as ribs, wings, winglets, blocks, etc. which are able to create secondary flow have been successfully used in conventional thermal systems to enhance heat transfer. Hence, in our previous work, Liu et al. [11] added some disturbing block elements, the so-called longitudinal vortex generators (LVGs), in rectangular microchannels. The experimental results indicated that the heat transfer and pressure loss were boosted simultaneously. The passive heat transfer enhancement methods creating secondary flow enhanced heat transfer by two types of vortices: transverse vortices and longitudinal vortices, as indicated by Jacobi and Shah [12]. These vortices ought to be distinguished from one another for their obviously different patterns. Moreover, longitudinal vortices could augment heat transfer locally and globally in steady flow, whereas global heat transfer enhancement induced by transverse vortices should be neglected for the same flow condition, as described by Fiebig [13].

Fiebig [13] experimentally and theoretically analyzed the overall performance of vortex generators whose forms were wings and winglets in both flat plate and channel flows. His analytical reports revealed that the longitudinal vortices were more efficient in heat transfer enhancement than the transverse ones, and winglets caused higher heat transfer enhancement than wings for identical parameters under study.

Fiebig et al. [14] systematically studied the performance of four different types of LVGs in minichannels with a rectangular cross-section for the Reynolds numbers ranging from 1000 to 2000 by using air as the working fluid. The aspect ratios and the attack angles of VGs were varied from 0.8 to 2 and from 10° to 60°, respectively. They found that the local heat transfer was augmented by several times; the mean heat transfer, more than 50%. Furthermore, they declared that the form drag induced by VGs was nearly proportional to the attack angle and the dynamic pressure of the flow.

Sohankar and Davidson [15] performed numerical investigation of flow and heat transfer characteristics for fluid flowing through rectangular channels with block-shaped VGs at various angles of attack. The Reynolds numbers involved in their study were from 400 to 1500. Their analytical data showed that the time- and area-averaged Nu numbers and friction factors were increased with increasing Re number and angle of attack. Also, they found that stronger and larger streamwise vortices were formed in the wake of VGs when thicker VGs were used.

Wu and Tao [16,17] theoretically and numerically studied thermo-fluidic characteristics of rectangular channels having LVGs with different attack angles and various geometric parameters including location, size, and shape. The working fluid was air. From their paper, one could observe that geometric parameters significantly affected the performance of LVGs. And the attack angle of 45° showed the best effectiveness in heat transfer augmentation, while Fiebig et al. [18] demonstrated that the optimal attack angle was 60°. It should be noted that Wu and Tao shed light on the fundamental mechanism of heat transfer enhancement by LVs, based on field synergy principle which was originally proposed by Guo et al. [19].

Wang et al. [20] experimentally researched the heat transfer and drag loss of both laminar and turbulent regimes in horizontal narrow rectangular channels with LVGs for water flow. The authors