International Journal of Heat and Mass Transfer 68 (2014) 224–233

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

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

Heat transfer in the microchannels with fan-shaped reentrant cavities and different ribs based on field synergy principle and entropy generation analysis

Y.L. Zhai, G.D. Xia [*], X.F. Liu, Y.F. Li

Key Laboratory of Enhanced Heat Transfer and Energy Conservation, Ministry of Education, College of Environmental and Energy Engineering, Beijiing University of Technology, Beijing 100124, China

A R T I C L E I N F O

Article history:
Received 2 June 2013
Received in revised form 24 August 2013
Accepted 24 August 2013
Available online 11 October 2013

Keywords:
Microchannel
Heat transfer enhancement
Field synergy principle
Entropy generation

A B S T R A C T

This study numerically investigates performance analysis of three types of microchannels and the results obtained are compared with the open literature. The results show that the effect of different types of ribs on the overall performance is evident. The thermal enhancement factor η of the microchannels F–R (with rectangular ribs) is always the lowest, depending on the range of Reynolds number. Furthermore, different comprehensive performance criteria, based on the first and second law of thermodynamics, are proposed to assess the relative merit of each microchannel. The microchannel F-Trp (with trapezoidal ribs) is appeared to be the most promising configuration when $Re < 300$, while the microchannel F–C (with circular ribs) has the best performance when $Re > 300$. According to field synergy principle, the heat transfer enhancement can be attributed to the good synergy between velocity vector and temperature gradient. Moreover, thermal boundary is disturbed after adding ribs and temperature different between the channel wall and fluid is small, thus the corresponding of irreversibility (entropy generation) reduces and heat transfer rate improves. The present study aims to provide alternative ways to evaluate the heat transfer performance of microchannels.

1. Introduction

Heat transfer enhancement in microchannels is of great significance for energy saving especially for the today's world where the coal and petroleum becomes scare. The roughness or turbulence promoters as a passive enhancement element are widely used in the microchannels [1]. Experimental and numerical studies of the rectangular/smooth microchannel with turbulence promoters, such as cavity, rib or cavity-ribbed roughness in a sidewall, are widely investigated in the open literature [2–7]. Distributions of such roughness along the wall inside are considered to be an effective technique to improve heat transfer rate as compared with a smooth microchannel. As known, the roughness can break the laminar viscous sublayer, create local fluid turbulence and reduce thermal resistance near the roughness, thus greatly enhancing the heat transfer effect [8]. Reviews of the heat transfer coefficient, pressure drop and thermal enhancement factor for different types of cavity-ribbed configurations on both experimental and numerical works have been examined by many investigators.

Eiamsa-ard and Promovonge [9] experimentally examined turbulent flows in periodically rib–grooved channel with different pitch ratios. They found that the thermal enhancement factor of triangular-rib with triangular-groove provided the highest value for all pitch ratios studied. Chai et al. [10], Xia et al. [11,12] studied the heat transfer performance of the microchannels with offset fan-shaped reentrant cavities, with aligned fan-shaped reentrant cavities and with triangular reentrant cavities. The results indicated that the Nusselt number and friction factor were higher than the smooth microchannel under similar test condition when $Re > 300$. However, because of stagnation in the cavity zone, there had little effect on heat transfer under low Reynolds number. Then, Xia et al. [13] subsequently proposed a new microchannel to solve this problem, which called the microchannel with fan-shaped reentrant cavities and internal ribs. They added the ribs between the cavities along the microchannel, and focused mainly on the effect of the relative rib height on the heat transfer enhancement. The results showed that the combined effect of cavities and ribs

---

[*] Corresponding author. Tel.: +86 1067392176; fax: +86 1067391983.
E-mail address: xgd@bjut.edu.cn (G.D. Xia).

0017-9310/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.08.086

Nomenclature

c_p	special heat capacity kJ/(kg K)
D_h	hydrodynamic diameter mm
e	rib height mm
f	friction factor
Fc	field synergy number
h	special enthalpy kJ/kg
h_{ave}	heat transfer coefficient W/(m^2 K)
h_b	height of baseplate mm
h_{ch}	height of channel mm
k_f	thermal conductivity of fluid W/(m K)
k_s	thermal conductivity of solid W/(m K)
L	length of channel mm
$\dot{m}$	mass flow rate kg/s
Nu	Nusselt number
N_s	augmentation entropy generation number
n	direction vector of heat flux
Δp	pressure drop Pa
Po	Poiseuille number
Pr	Prandtl number
q'	Heat flux per unit length W/m
Q	total heat input W
Re	Reynolds number
s	special entropy kJ/(kg K)
$\dot{S}'''_{gen}$	volume entropy generation rate W/(m^3 K)
$\dot{S}'''_{gen,\Delta p}$	frictional entropy generation rate W/(m^3 K)
$\dot{S}'''_{gen,\Delta T}$	heat transfer entropy generation rate W/(m^3 K)
$\dot{S}_{gen}$	total entropy generation rate W/K
u_m	mean velocity m/s
u	velocity in x-component m/s
U	velocity vector m/s
V	volume of computational zone m^3
v	velocity in y-component m/s
W	pitch of channel wall mm
W_{ch}	weight of channel mm
w	velocity in z-component m/s

Greek symbols

α, β	field synergy angle, °
η	thermal enhancement factor
ρ	density kg/m^3
μ	dynamic viscosity kg/(m s)
τ_w	shear stress of wall Pa

Subscript

ave	average
b	baseplate
gen	generation
m	mean
s	solid
w	wall

had better performance than that of individual cavity or rib when Reynolds number ranging from 300 to 600.

As known, the use of roughness is typically accompanied by an increase in frictional losses which leads to more power consumption. The design of the roughness configuration should be addressed by a certain criterion, which must consider both heat transfer enhancement and the corresponding increase in pressure drop. Several criteria have been applied to assess the comprehensive performance in microchannels. Performance evaluation criterion (PEC) is a widely accepted method to evaluate the comprehensive effect of heat transfer coefficient and friction factor, which is presented by Webb [14]. The author defined the performance benefits as an enhanced channel relative to a reference channel under the same test condition. The thermal enhancement factor η is the ratio of the heat transfer coefficient and friction factor of the reference channel (smooth channel) over that of the current channel (enhanced channel). An alternative approach, based on the first law of thermodynamics to evaluate the merit of augmentation techniques, is called field synergy principle, which is proposed by the team of Guo et al. [15]. They indicated that the heat transfer mechanism was related to the angles between the streamlines and the isotherms, as well as the synergetic relation among velocity vector, velocity and temperature gradient. They also proposed a new non-dimensional number, filed synergy number Fc, to assess the comprehensive performance in the convective heat transfer process. The larger the synergy number Fc, the better the synergy between the velocity and temperature field is, thus greatly enhancing the heat transfer effect. Then, a lot of experimental and numerical studies have been conducted to explain the physical mechanism of the convective heat transfer using this principle [16–20]. Although the energy is conserved in the heat transfer process, the useful energy (exergy or available work) is destructed due to the irreversibility of flow friction and heat transfer across the wall-to-fluid temperature difference. So the second law analysis of the irreversibility is important for conserving useful energy. Entropy generation analysis, based on the second law of thermodynamics, is another method to investigate the heat transfer performance, which is proposed by Bejan [21]. The method is focused mainly on the irreversibility caused by the process of heat transfer and flow in ducts. The augmentation entropy generation number N_s, is defined as the ratio of the entropy generation rate between the enhanced channel and reference channel. The value of N_s less than unity is considered as thermodynamically advantageous.

As stated above, many studies have been investigated the heat transfer performance of different types of roughness in the microchannels. However, to the author's knowledge, the physical mechanism of heat transfer enhancement by using cavities or ribs is seldom reported. Physical understanding of those microchannels is a fundamental issue in designing and optimizing the efficient micro heat sinks.

The main aim of this report is to investigate the physical mechanism of the enhanced microchannel and to assess the effect of different types of ribs on the heat transfer performance based on different evaluation criteria. This study is organized into three parts. In the first part, the mathematical model of the microchannels is validated. In the second part, the physical mechanism of a combination of cavities and ribs in heat transfer enhancement is studied in detail. Lastly, three evaluation criteria mentioned above have been applied to analyze the performance of those microchan-