International Journal of Thermal Sciences 135 (2019) 44–60

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Experimental and numerical investigations of fluid flow and heat transfer in a bioinspired surface enriched microchannel

Prasenjit Dey, Gaurav Hedau, Sandip K. Saha*

Department of Mechanical Engineering, Indian Institute of Technology Bombay, Mumbai, 400 076, India

ARTICLE INFO

Keywords:
Bioinspired surface
Rectangular microchannel
Heat transfer
Friction factor

ABSTRACT

In this paper, experimental and numerical studies of fluid flow and heat transfer characteristics of novel fish scale bioinspired structures on the bottom surface of microchannel to enhance heat transfer are presented. Deionized water is selected as the working fluid. A three-dimensional numerical model is developed to analyse conjugate heat transfer in the microchannel, and the model is validated with the experimental results obtained from a copper microchannel of hydraulic diameter of 193.5 μm and length of 20 mm for three different Reynolds numbers and a constant bottom heat flux of 50 W/cm^2. Further the numerical model is extended to study the effect of several geometrical parameters on the thermohydraulic performance of microchannel. It is found that the bioinspired surface can enhance the convective heat transfer compared to the plain microchannel, whereas the pressure drop is found less for fish scale structure with dimensionless inclination height of 0.026. The friction factor for the fish scale inclination height of 0.026 reduces by maximum 5% and the Nusselt number increases by maximum 14% as compared to those quantities for the plain microchannel. Further increment in the inclination height increases the heat transfer rate and friction factor than the plain microchannel. The maximum value of the performance evaluation criteria is found as 1.75 at inclination height of 0.26 and Re = 1050. Correlations of Nusselt number and Poiseullie number are developed for this type of microchannel.

1. Introduction

Experimental and numerical studies of micro-scale devices are receiving attention of the scientific community from the last few decades due to the rapid development of microelectronics, bio and nanotechnologies. Several of these micro and nano scaled devices generate high heat flux, which presents challenge to keep the device temperature under the critical limit. In this context, microchannels are recognized as one of the crucial research areas on the micro-fluidic systems because of its substantial cooling characteristics in high power magnets, accelerator targets, material processing and manufacturing industries, advanced thermal management systems, and high computation operations in computers *etc.* [1]. For dissipating high heat fluxes associated with micro-devices, the heat transfer coefficient is required to be high, which can be achieved through microchannel due to its higher heat transfer surface area to fluid volume ratio compared to other macroscale systems. Till date, numerous experimental and numerical studies on microchannel are performed since its introduction by Tuckerman and Peace [2]. As the primary goal of using the microchannel is to dissipate more heat, various heat transfer enhancement methodologies are developed to improve the heat transfer performance of microchannel for better cooling of the micro-devices [3]. Potential approaches are interruption of thermal boundary layer, mixing between hot and cold fluids and flow separation to augment the heat transfer rate in microscale [4].

The combination of transverse micro-chamber and parallel longitudinal microchannel developed by Xu et al. [4] was studied by both the numerical and experimental approaches. They noted that the microchamber allows the redevelopment of thermal boundary layer leading to the enhancement in heat transfer. A numerical study in a wavy microchannel was studied by Gong et al. [5] and the authors concluded that heat transfer can be enhanced by redeveloping the thermal boundary layer. A significant enhancement in the heat transfer rate can be achieved by introducing the wavy surface inside the straight microchannel [6]. Numerical analysis was performed by Hong and Cheng [7] on an offset strip-fin microchannel network heat sinks. Authors concluded that the two major factors caused the enhancement of the heat transfer rate are, *(i)* mixing between the cold and hot coolant and *(ii)* interruption of thermal boundary layer. A better mixing between the hot and cold fluids can augment the convective heat transfer rate, thereby reducing the thermal resistance, which can be obtained by introducing multiple passive microstructures in a plain channel [8].

* Corresponding author.
E-mail address: sandip.saha@iitb.ac.in (S.K. Saha).

https://doi.org/10.1016/j.ijthermalsci.2018.08.042
Received 3 April 2018; Received in revised form 7 August 2018; Accepted 27 August 2018

Nomenclature

c_p	Specific Heat, (J/kg.K)
D_h	Hydraulic diameter $\left(\frac{2WH}{(W+H)}\right)$, m
f	Friction factor
H	Channel height, m
H_f	Horizontal gap of fish scale, m
I_f	Inclination height of fish scale, m
k	Thermal conductivity, (W/m.K)
L	Channel length, m
$\mathscr{L}$	Arc length of the solid surface, m
n	Number of fish scales
Nu	Nusselt number $\left(\frac{h_{avg}D_h}{k_l}\right)$
P	Pressure, bar
Po	Poiseullie number, fRe
q''	Heat flux, W/m^2
Re	Reynolds number $\left(\frac{\rho U_\infty D_h}{\mu}\right)$
S_f	Scale slant height, m
S_p	Stream-wise distance between the scales, m
T	Temperature, K
U	Velocity, m/s
V	Voltage, Volt
V_f	Vertical height of fish scale, m
W	Channel width, m
W_f	Width of scale, m

Greek symbols

A	Inclination angle
P	Density, (kg/m^3)
M	Dynamic viscosity, (kg/m.s)
B	Aspect ratio, H/W
Φ	Variable
H	Unit normal vector on the solid surface

Subscript

l	Fluid
f	Fish scale
m	Mean value
s	Solid
amb	Ambient condition
avg	Average value
w	Wall
∞	Free stream
O	Values for plane channel
In	Inlet
Out	Outlet

Several researchers to study the behaviour of fluid flow and heat transfer in microchannel with longitudinal vortex generator to enhance the heat transfer rate [9–11] performed a number of numerical and experimental investigations. However, pressure drop across the microchannel with longitudinal vortex generator is comparatively high. Moreover, numerous investigations were conducted in microchannel using different nanofluid to enhance the heat transfer rate for better thermal applications [12–16].

The overall performance criteria of a microchannel can be enhanced by introducing porous medium, which results in the reduction of pressure drop and the enhancement of convective heat transfer rate [17–19]. The effectiveness of these approaches also depends on the surface roughness, which cannot be neglected if the relative roughness height is larger than 1% of the channel hydraulic diameter in microchannels [20,21]. Hu et al. [22] numerically studied the effect of three dimensional rectangular prisms rough surface in a microchannel and concluded that the velocity and pressure drop are greatly influenced by the geometrical parameters of the roughness. A two-dimensional randomly generated roughness peak was modelled by Giulio and Paola [23] and studied numerically with a conclusion that flow resistance is higher in roughed channel compared to that in the plain channel, however heat transfer is quite similar in both the channels. A three-dimensional model for triangular, trapezoidal and rectangular shaped roughness along the channel was proposed by Rawool et al. [24]. They observed that the friction factor and Reynolds number (Re) are inversely proportional to each other, which shows a substantial impact of the roughness geometry parameters on flow behaviour. A numerical analysis of thermal performance in microchannels with two-dimensional and three-dimensional randomly generated roughness was accomplished by Guo et al. [25] and found that both the flow behaviour and heat transfer are sensitive to the surface morphology of roughness. The effect of structured roughness or extended surface on the fluid flow and heat transfer in microchannel was numerically studied by Yadav et al. [26]. A circular type of extended surface up to a certain height (less than the overall channel height) was introduced on the bottom surface of the channel. Authors noted that an enhancement of 160% in heat transfer was achieved compared to a smooth channel by using the extended surface with acceptable pressure drop penalty.

Few of the structured and hierarchical extended surfaces are inspired by biological surfaces (biomimetic). Several researchers had extensively studied the well-known bioinspired (lotus leaf, rice leaf, rose petals etc.) surface in microchannel to enhance single phase heat transfer performance [27–39]. For single phase laminar water flow in microchannel with enhanced surface made of square posts and holes, transverse and longitudinal grooves, Cheng et al. [29] numerically investigated the frictional and thermal performance in the range of $Re = 1$ to 1000. It was found that the Nusselt number in microchannel with enhanced surface increases consistently with Re compared to that in the smooth channel and the Poiseullie number shows incremental behaviour with Re. An experimental study of friction factor and heat transfer characteristics of water flowing in a superhydrophobic (a typical roughness of 22.1 μm) tube was performed in a range of $Re = 3000$ to 11000 by Lv and Zhang [30]. They concluded that the friction factor and Nusselt number of superhydrophobic tubes were less than those of smooth tubes at the same Reynolds number. A leaf vein inspired microchannel was analysed by using a three dimensional numerical model by Luo et al. [32]. Three different surface geometries, such as F. virens, *P. rubra* and H. patens were studied and found that these surfaces can provide excellent heat transfer characteristics with a smaller volume while the ability in mass transfer reduces slightly. The applications and advantages of such bio inspired surfaces were studied for anti-icing, drag reduction, boiling heat transfer, condensation, self-cleaning property [37–39].

It can be noted that most of the studies on bio-inspired microchannel were carried out for the two phase flow, however very few literature is available for single phase flow and also the surface patterns are limited to the micro pillar or grooves, patterned nano/micro structured roughness, random roughness. Apart from microscale system, several other bio-inspired surfaces, such as butterfly wings, peacock feathers, shark skin, upper wing surfaces of insects, fish scales were used in different advanced macroscale applications such as adhesion, hydrophobicity, multispectral response, energy scavenging, thermal regulation, anti-biofouling [38,39]. The bio inspired surface fish scale specially shark skin was used in single phase heat exchanger and wind turbine to reduce the friction factor and consequently to enhance the efficiency of the system by virtue of its micro/nano