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Thermo hydraulic performance analysis of twisted sinusoidal wavy microchannels

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ABSTRACT

Numerical simulation of fully developed laminar fluid flow and heat transfer in a twisted sinusoidal wavy microchannel is presented. Twisted channel is a sinusoidal rectangular channel with progressive rotation of its cross sectional geometry in stream wise direction. 3-D, unsteady, incompressible, laminar flow model with constant wall temperature and heat flux boundary conditions are simulated using SIMPLE algorithm based finite volume method. Computational procedure has been validated using available experimental data. Extensive computations have been performed to study the thermo-hydraulic performance of twisted wavy microchannels with various amplitude to wavelength ratios and twist ratios for $300 \leq Re \leq 700$. Results show that the twisted wavy microchannels can substantially enhance heat transfer performance with minimal pressure drop for low Re number regime compared to sinusoidal microchannels. Twisted channels of higher aspect ratio and lower waviness produced heat transfer enhancement of around 30% compared to sinusoidal wavy microchannels.

1. Introduction

Research on laminar flow heat transfer enhancement in microchannels has attained paramount interest due to the overwhelming demand for passive performance augmentation of compact heat exchangers and electronic cooling modules. Many macro and micro-intricate flow passage options have been experimented in recent past for developing heat exchangers with superior thermo-hydraulic performance. It is well known that the generation of flow features such as recirculation regions with transverse vortices, disruption of flow path with periodic chaotic advection, thinning of boundary layer, etc. enhance heat and momentum transfer. Heat transfer enhancement and associated pressure drop are harmonious cohorts that invite many challenges in the development of efficient and compact heat exchanging flow passages. This has opened up many opportunities to the heat transfer research community to foster the development of novel flow passages having excellent heat transfer characteristics with minimal pressure drop. Manufacture of micro tortuous flow passages is possible today with the advent of micro fabrication and additive manufacturing techniques for metals. However, manufacturing of microchannels with the desired surface finish is difficult at present due to large surface roughness associated with the currently available techniques. In addition, the roughness removal technologies have limitations in using it for small and twisted passages.

Objective of the present study is to computationally investigate the thermo-hydraulic performance of a twisted wavy microchannel. This novel microfluidic wavy passage has given a periodic switching of cross sectional geometry in stream wise direction as shown in Fig. 1. This geometry may augment heat transfer substantially by maintaining low friction factor in the low Re regime compared to their parental counterparts. This is achieved by the asymmetry of secondary flow induced by the progressive switching of cross-sectional area while carrying the fluid along a wavy path. Thus, sharp temperature gradients can be maintained near to the wall without the heavy penalty of pressure drop.

Research on thermo-fluidics in periodic micro passages has become well established and relevant literature includes a large number of publications. Goldstein and Sparrow [1] carried out pioneering experiments in a corrugated wall channel for both laminar and turbulent regime to estimate local and average heat transfer characteristics and found that separation and reattachment can significantly augment them. Gschwind et al. [2] reported that the flow instability in corrugated channels depended strongly on the duct height; in a small range of Görtler numbers and instability traverses the entire duct only for small duct heights. Rush et al. [3] observed that the instabilities and associated macroscopic mixing are major reasons for heat transfer enhancement in wavy channels. They observed that heat transfer enhancement was more near the exit and later it shifted toward the channel entrance with increasing Re due to the relocation of the instability. Studies of Metwally and Manglik [4] for sinusoidal corrugated-plate channels indicated that transverse vortices generated by the

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Nomenclature

Letters

A	Amplitude of the channel[μm]
A_c	Area of cross section [m^2]
b	Height of the channel cross section [μm]
c_f	Specific heat of fluid [$Jkg^{-1}K^{-1}$]
D_h	Hydraulic diameter [μm]
f	Friction factor
h_x	Local Heat transfer coefficient [$Wm^{-2}K^{-1}$]
$\bar{h}$	Average heat transfer coefficient [$Wm^{-2}K^{-1}$]
j	Colburn factor
k	Thermal conductivity [$Wm^{-1}K^{-1}$]
Nu	Nusselt Number
p	Pressure [Nm^{-2}]
q	External heat flux [Wm^{-2}]
S	Twist pitch [μm]
T_x	Local bulk fluid temperature [K]
T_a	Volume averaged bulk fluid temperature [K]
T_{wx}	Perimeter averaged surface temperature [K]
t	Time [s]
u	Velocity [ms^{-1}]
$\bar{U}$	Average streamwise velocity [ms^{-1}]
V	Volume of the fluid [m^3]
R	Shear strain rate tensor
x,y,z	Cartesian coordinates
w	Breadth of channel cross section [μm]

Greeks

α	Thermal diffusivity [$m^2\ s^{-1}$]
β	Aspect ratio
δ	Twist ratio
ε	Goodness factor
λ	Wave length [m]
μ	Dynamic viscosity [Pa s]
ν	Kinematic viscosity [$m^2\ s^{-1}$]
ρ	Density [kgm^{-3}]
ς	Vorticity [s^{-1}]
θ	Dimensionless temperature

Subscripts

f	fluid
s	Solid
sw	Simple wavy channel
tw	Twisted wavy channel
w	Wall

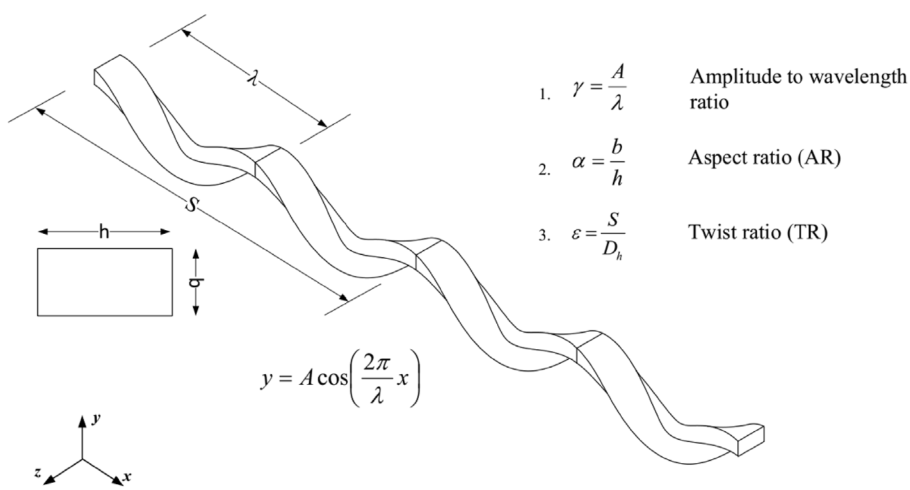

Fig. 1. Geometrical aspects of the twisted sinusoidal wavy microchannel.

corrugations grew with wall waviness and flow Re. Tanda and Vittori [5] presented numerical results of laminar fully developed flow in two-dimensional wavy channel and found that maximum local heat transfer occurred near the crests of the wavy wall. Volker and Vanka [6] simulated two-dimensional serpentine channel and found that the heat transfer as well as the pressure drop increased with decreasing channel height. Sui et al. [7]showed that the periodic change in direction of centrifugal force generated Dean vortices. Many researchers attempted detailed parametric studies of flow and geometrical factors such as cross section, amplitude, and waviness of wavy channel that affected its thermo-hydraulic performance. Studies of Mohammed et al. [8] indicated that the friction factor increased with increase in amplitude of wavy channel. Recently Al-Neama et al. [9] conducted experimental and numerical investigation in four different serpentine microchannels and found that they could give heat transferenhancement up to 35% and 19% reduction in total thermal resistance compared to straight rectangular microchannels. Sakanova et al. [10] also made similar observations and found that thermal resistance was less for wavy channels with higher amplitude and shorter wavelength. Wang and Chen [11] numerically analysed an array of wavy-wall channel and their findings also showed that the heat transfer enhancement is significant for larger value of amplitude to wavelength ratio at higher Re. Rostami [12] investigated conjugate heat transfer in wavy wall microchannels with constant heat flux boundary condition and suggested optimum geometrical parameters such as aspect ratio, wall thickness, amplitude and wavelength. It can be summarized that the thermal performance of wavy channels are found to be more for high Re flows and pressure drop increases with increase in amplitude and decrease in wavelength. Therefore, wavy micro-passages with varying cross-sectional area may be a promising alternative for heat transfer performance improvement in low Re flows with minimal pressure drop.

Periodic changes in cross sectional area of flow path along streamwise direction for sinusoidal channels also attributes enhancement. Numerical studies of Patankar et al. [13] indicated the presence of strong blockage effects and massive recirculation zones in ducts of periodically varying cross-section. Tatsuo et al. [14] analysed the mass