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Impact of tortuous geometry on laminar flow heat transfer in microchannels

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ABSTRACT

An experimental investigation of the hydrodynamic and heat transfer characteristics of water flowing through tortuous microchannels for Reynolds numbers ranging from 50 to 900 has been carried out. The microchannels have semi-circular cross-sections (diameter 2 mm) and follow zigzag or sinusoidal pathways consisting of at least five repeating units. Conjugate heat transfer simulations in a straight channel are carried out to understand the complex thermal behaviours present in the current experimental design and to validate the experimental approaches. The integrated measurements of fluid flow and heat transfer offer capabilities for characterising the thermohydraulics of wavy microchannels. Experimental results show that significant heat transfer enhancement is achieved in wavy channels compared with the equivalent straight channel, although an increased pressure-drop penalty is also observed. A detailed flow dynamics study shows that the flow recirculation and secondary flow structures (Dean vortices) induced by the bend help to increase the heat transfer rates. The impact of geometrical parameters on flow and heat transfer performance is assessed. In addition, the stackability of channels on a plate structure is considered. Zigzag channel configurations which provide high heat transfer intensification, are well suited for the use in compact plate heat exchangers due to their significant heat transfer enhancement, as well as good stackability.

1. Introduction

Over the last few decades, various innovations have taken place to achieve intensification of heat transfer in terms of energy saving, sustainable development, thermal control, compactness, etc. Micro-structured devices are finding evermore industrial applications where high rates of heat transfer are required in a compact space, such as compact heat exchangers, micro-reactors and electronic cooling devices. Tortuous microchannels present great potential to provide enhanced heat exchanger performance, where secondary flows (Dean vortices) [1] in the channel cross-section induced by flow around bends are of critical importance and can be used as a means of process intensification.

For tortuous channels, the geometrical parameters and Reynolds number are the main factors governing the pressure drop and heat transfer characteristics. It has been shown that the channel waviness produces a secondary flow pattern that is made up of multiple counter-rotating vortices in the flow cross-section, and their magnitude and spatial coverage increase with Reynolds number. This significantly enhances the overall heat transfer coefficient compared with the straight counterpart, however, this is accompanied by an increase in the friction factor, meaning higher pumping power is required [2–5].

Heat exchanger design is dependent on the choice of the channel geometry, as the geometric configuration influences greatly both the hydraulic and thermal performances. To identify the suitability of a particular tortuous geometry applied in a heat exchanger, various evaluation criteria have been proposed for selecting and optimising heat exchanger passage geometries. A widely used approach is that of London [6] who proposed "surface flow area goodness factor" to evaluate the heat transfer and pressure drop characteristics together. However, it is still challenging to define how to optimise the choice since in most selection processes there are several, often conflicting, criteria that have to be met with regard to the exchanger. A considerable amount of work has been performed to develop more comprehensive evaluation/ranking approaches by taking heat exchanger core volume, surface compactness, and other design preferences into account [7–9]. Recently, Zheng et al. [10] demonstrated graphically a composite design specification which can be calculated simply from the design inputs (fluid properties, flow rates, the allowable pressure drops, and the terminal fluid temperatures) and channel pressure loss and heat transfer characteristics to evaluate the performance

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Nomenclature

A	channel amplitude (m), area (m^2)
$\hat{c}_p$	fluid specific heat capacity (J kg^{-1} K^{-1})
d	channel diameter (m)
d_h	hydrodynamic diameter (m)
e_A	area utilisation
e_f	relative pressure-drop penalty
e_{Nu}	heat transfer enhancement
f	Fanning friction factor
h	heat transfer coefficient (W m^{-2} K^{-1})
h_{loss}	heat loss coefficient (W m^{-2} K^{-1})
i_A	heat transfer intensification
I	current (A)
k	thermal conductivity (W m^{-1} K^{-1})
l_x	axial location from the start of the heating section (m)
L	half-unit length (m), length (m)
L_p	overall path length (m)
$\dot{m}$	mass flow rate (kg s^{-1})
Nu	Nusselt number, $Nu = hd_h/k$
P	channel cross-sectional perimeter length (m)
ΔP	pressure drop (Pa)
$\dot{q}_w$	wall heat flux (W m^{-2})
Q_f	heat transferred to the fluid (W)
Q_{in}	total power input (W)
Q_{loss}	heat loss to the environment (W)
R	thermal resistance (m^2 K W^{-1})
R_c	radius of curvature (m)
Re	Reynolds number, $Re = \rho u_m d_h/\mu$
$\dot{S}$	volumetric heat generation rate (W m^{-3})
S_0	channel axial path length of one unit (m)
t	time (s), wall thickness (m)
T	temperature (K)
$\bar{T}_w$	peripherally-averaged wall temperature (K)
u_m	mean fluid velocity (m s^{-1})
V	voltage (V)

Greek symbols

θ	channel bend angle (°)
ρ	density (kg m^{-3})
μ	dynamic viscosity (Pa s)

Subscripts

a	ambient
b	bulk
c	channel
G	glass
h	heater
i	inner surface
in	inlet
M	metal
o	outer surface
out	outlet
str	straight channel
w	wall, wavy channel
x, y, z	x, y, z coordinate

of different enhanced surfaces without undertaking detailed design work. These evaluation methods will benefit the practical heat exchanger design process for early size and shape assessments, surface selection and optimisation of the design specification.

In order to characterise heat exchanger performance, knowledge of the frictional and heat transfer characteristics of the applied channels is required. Numerous authors have analysed flow patterns and the conditions for the appearance of instabilities and chaos in the flow within wavy microchannels, especially for corrugated and converging–diverging plate channels. More recent works of Mohammed et al. [11], Ghaedamini et al. [12,13], and Xie et al. [14,15] numerically studied wavy microchannels in heat sinks for high heat flux applications, such as electronics cooling. The effect of various geometrical parameters on the thermal performance and flow fields were also discussed. Different mechanisms that affect the thermal performance of the microchannel design were addressed in [12]. They indicated that chaotic advection occurred in wavy channels enhanced heat transfer as a result of better mixing, however, counter-rotating vortices created in the trough region had an adverse effect on heat transfer. Focusing on compact heat exchangers based on a plate structure, fluid flow and heat transfer in wavy microchannels have been studied numerically by our group [5,16–19]. Significant heat transfer enhancement was also found in these narrowly-spaced passages accompanied by acceptable pressure penalties.

While the thermohydraulics in wavy microchannels have been studied extensively in a numerical fashion, experimental studies are very limited due to the technical difficulties of making accurate measurements in micro-scale flows. Several experimental studies have been performed to characterise flow and heat transfer in wavy channels. Xiong and Chung [20,21] applied the micro-Particle Image Velocimetry (micro-PIV) technique to obtain the detailed velocity vector field in serpentine microchannels with mitre bends. Sui et al. [4] measured the friction factor and overall Nusselt number experimentally in sinusoidal microchannels with different wave amplitudes. Karale et al. [22] carried out flow and heat transfer experiments in a serpentine channel and then applied computational fluid dynamics (CFD) to understand the effect of various geometrical parameters on heat transfer enhancement. Anxionnaz-Minvielle et al. [23] performed experimental study of the influence of the geometrical parameters and characteristic size of a wavy channel on pressure drops, heat and mass transfer performance and derived correlations depending on the channel design. They studied the detailed flow mechanisms in these corrugated channels with the aid of CFD simulations. Amongst the limited experimental studies, none of them connected the flow behaviour and heat transfer performance directly through integrated measurements which could provide both velocity and temperature information. Most of the studies presented either flow field or overall heat transfer performance and relied on the computational tools to get more detailed information. In addition, it is important to note that convective heat transfer in microchannel systems might be coupled with significant conduction effects within the substrates, which is called a conjugate problem. Most of the previous experimental results were based on measurements performed outside of the channels and did not consider the possible conjugate heat transfer effect in microchannels.

To fully understand the governing physical mechanisms for heat transfer enhancement in wavy microchannels, integrated tools for direct flow observation and heat transfer measurements are required. In this study, experimental techniques are developed to perform flow field visualisation and heat transfer measurements in microchannels. Micro-PIV techniques are employed to determine velocity fields. A numerical model is developed to understand