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An experimental study of flow friction and heat transfer in wavy microchannels with rectangular cross section

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ABSTRACT

Experimental investigation has been conducted on the flow friction and heat transfer in sinusoidal microchannels with rectangular cross sections. The microchannels considered consist of ten identical wavy units with average width of about 205 μm, depth of 404 μm, wavelength of 2.5 mm and wavy amplitude of 0–259 μm. Each test piece is made of copper and contains 60–62 wavy microchannels in parallel. Deionized water is employed as the working fluid and the Reynolds numbers considered range from about 300 to 800. The experimental results, mainly the overall Nusselt number and friction factor, for wavy microchannels are compared with those of straight baseline channels with the same cross section and footprint length. It is found that the heat transfer performance of the present wavy microchannels is much better than that of straight baseline microchannels; at the same time the pressure drop penalty of the present wavy microchannels can be much smaller than the heat transfer enhancement. Conjugate simulation based on the classical continuum approach is also carried out for similar experimental conditions, the numerical results agree reasonably well with experimental data.

1. Introduction

Since the classical work of Tuckerman and Pease [1], direct liquid cooling incorporating microchannels has drawn more and more attention [2–7]. Microchannel heat sinks have high heat removal ability; also they could be directly integrated into the heat-dissipating devices. However, there are still some challenges to overcome. With regard to single-phase cooling, due to the reduced feature size of microchannels, high flow rates will cause a sharp increase in pressure loss. The coolant flow through microchannels is always in laminar flow regime. A conventional microchannel heat sink generally employs straight channels, the fluid mixing is poor and the heat transfer is thus not efficient.

Various approaches have been proposed to enhance the heat transfer performance in microchannels, for example microchannel heat sinks based on fractal-like branching channels networks [8,9], tree-shape microchannels nets [10], coiled or even hybrid-geometry channels [11]. In fact, convective heat transfer in the laminar flow region strongly depends on fluid mixing. One promising flow mechanism for enhancing fluid mixing involves the use of Dean vortices. It is well known that when liquid flows through curved passages at sufficiently high Reynolds numbers, secondary flows (Dean vortices) may be generated due to centrifugal forces. The secondary flows promote rotation of fluid elements in the spanwise plane of the curved passage, which in turn causes stretching and folding of the fluid elements, thus improving the mixing as well as heat transfer. This mechanism has been employed by many researchers for mixers [12,13] and heat transfer enhancement [14–17]. Recently, Fletcher and coworkers [18–23] performed systematic numerical studies of fully developed flow and heat transfer in periodic serpentine channels with various foot-path and cross-section shapes. Manglik et al. [24] numerically investigated the forced convection in wavy-plate-fin channels under periodically developed air flow conditions. Their simulations focused mainly on the steady laminar flow regime. It was found that Dean vortices and more complex vertical flow patterns emerge when the liquid coolant flows through the bends. The heat transfer performance could be greatly enhanced over straight channels with the same cross section; at the same time the pressure drop penalty was much smaller than the heat transfer enhancement.

Motivated by previous studies [11–24], the present authors proposed to improve the performance of microchannel heat sinks by replacing the conventionally employed straight channels with sinusoidal channels [25]. Furthermore, it was proposed to vary the relative wavy amplitude of the microchannels along the flow direction for various practical purposes. Three-dimensional numerical simulation was conducted to investigate the liquid-water flow and heat transfer in such wavy microchannels with

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Nomenclature

A	wavy amplitude (m)
A_b	base area of copper block (m^2)
A_{cb}	area of bottom wall of a single channel (m^2)
A_{cs}	area of one side wall of a single channel (m^2)
c_p	specific heat (J kg^{-1} K^{-1})
D	Hydraulic diameter (m)
E_f	pressure drop penalty factor
E_{nu}	heat transfer enhancement factor
f	friction factor
h	average heat transfer coefficient (W m^{-2} K^{-1})
H	channel depth (m)
k	thermal conductivity (W m^{-1} K^{-1})
L	wavelength of one wavy unit (m)
L_t	total length of a channel (m)
N	number of channels
Nu	average Nusselt number
p	static pressure (Pa)
q	heat power (W)
q''	heat flux (W m^{-2})
Q	volumetric flow rate (m^3 s^{-1})
Re	Reynolds number
s	distance (m)
S_c	channel width (μm)
S_w	wall thickness (μm)
T	temperature (K)
T_m	mean fluid temperature (K)
T_w	average wall temperature (K)
U	average flow velocity (m s^{-1})
x	x-coordinate (m)
y	y-coordinate (m)
z	z-coordinate (m)

Greek symbols

μ	fluid viscosity (kg m^{-1} s^{-1})
ρ	fluid density (kg m^{-3})
η	fin efficiency

Subscripts

c	channel
f	pressure drop penalty factor
m	mean
nu	heat transfer enhancement factor
t	total
w	wall

rectangular cross sections [25]. The simulation results showed that the heat transfer performance of the wavy microchannels is much more superior to that of straight channels with the same cross section and total length; at the same time, the pressure drop penalty could be much smaller than the heat transfer enhancement. The underlying physical mechanism was revealed by detailed flow field analysis, which showed that the spatial evolution of Dean vortices along the flow direction can lead to chaotic advection that greatly enhances fluid mixing. In fact, recent parametric numerical study of flow and heat transfer in wavy microchannels by Gong et al. [26], shows that at intermediate Reynolds number when Dean vortices do not form, the overall performance of wavy channels can still be much better than that of straight channels for certain wavy geometries.

To the best of our knowledge, the heat transfer performance of microchannel heat sinks employing similar wavy microchannels has thus far not been experimentally investigated in a systematic fashion. Rush et al. [27] experimentally studied the flow and heat transfer in sinusoidal passages with much larger dimensions. The geometrical parameters considered, mainly the aspect ratio, relative wavy amplitude and relative channel width, are very different from those studied by the present authors [25]. Curvature induced lateral vortices were observed in the trough of the wavy profiles [27], and thus the fluid mixing mechanism may be different from that of narrowly-spaced and low-amplitude channels considered by the present authors [25], in which the fluid mixing was mainly achieved by the spatial evolution of Dean vortices along the flow direction.

In the present study, experimental investigation is carried out on liquid-water flow and heat transfer in sinusoidal microchannels with a rectangular cross section. It should be noted that for flow in microscale, additional factors like surface roughness etc. may have significant effect on the flow field and heat transfer performance. These factors are always neglected by numerical simulation. Also, steady laminar flow model was assumed and the boundary conditions prescribed in numerical study may not be exactly the same as real conditions [25]. These make experimental validation necessary. The microchannels considered in the present study consist of ten identical wavy units with averaged width of 205 μm, depth of 404 μm, wavelength of 2.5 mm and wavy amplitude varying between zero and 259 μm. Each test piece is made of copper and contains 60–62 wavy microchannels in parallel. The experiments are conducted with deionized water as the coolant and the Reynolds numbers considered range from approximately 300 to 800. The experimental results, namely the overall Nusselt number and friction factor, for wavy microchannels are compared with those of straight baseline channels with the same cross section and footprint length. The wavy microchannels in the present experiments have a nearly constant width along the channel center line, and thus are geometrically different from channels considered in previous simulations [25], which were formed from two parallel wavy walls and the fluid experiences a converging-diverging effect along the flow direction. Due to different geometries, new conjugate heat transfer simulation becomes necessary and is conducted for similar experimental conditions. The simulation results are compared with experimental data.

2. Experimental set-up and procedures

Fig. 1 presents the schematic diagram of the experimental setup, which is largely similar to that used by Lee et al. [6] for experimental investigation of heat transfer in straight microchannels with rectangular cross sections. Deionized water from a holding tank with volume of about 40 L is driven through the test loop with a gear pump (Cole-Parmer 74014-55). The fluid first encounters an inline 7 μm filter (Swagelok SS-8F-7). The filter element is replaced every few weeks to prevent fouling. The deionized water then passes through a turbine flow meter (McMillan 104 6T) with a measurement range of 100–1000 ml/min. The fluid subsequently enters the test section, which contains the microchannel heat sink. Heated water exits the test section and enters a liquid-to-air heat exchanger (Thermatron 735SPC2A01), where it is being cooled, before returning to the water tank. The fluid is then recirculated through the flow loop.