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Convective heat transfer and mixing enhancement in a microchannel with a pillar

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ABSTRACT

An experimental study of heat transfer in microchannel with pillar/pillars was conducted with air. Area-averaged temperature was measured by a $1 \times 1\ mm^2$ resistance temperature detector (RTD), and data were collected over the range $100 \leqslant Re \leqslant 5600$. The microchannel with a pillar had a heat transfer coefficient that was twice that of the channel without a pillar. Among the three geometric shapes of pillar studied, triangular pillar performed the best with $17.7 \leqslant \langle Nu \rangle \leqslant 88.9$. Micro particle image velocimetry (μPIV) was used to measure the velocity field in the mircochannel and turbulent kinetic energy (TKE) calculation provided a measure of flow mixing. It was shown that TKE is closely related to the thermal performance and can be used to predict the Nusselt number.

1. Introduction

With the advances of microelectromechanical systems (MEMS) technology, heat transfer in microchannel has been extensively studied in recent years. As part of this effort, micro-scale pin fins were explored as a possible passive heat transfer enhancement technique. Many studies [1–12] have shown that, besides the increase of the surface area, the addition of pin fins in a microchannel allows better flow mixing and as a result, enhanced heat transfer.

An analytical heat transfer analysis over a micro pin fin heat sink suggested that very high heat fluxes can be dissipated at low wall temperature and the thermal performance of flow across a pin fin array is superior to that of a plain microchannel [1]. Kosar and Peles [2] experimentally obtained heat transfer coefficients comparable to flow boiling on micro heat sink, and found that the dependence of the Nusselt number on the Reynolds number was more notable than that for convectional-scale correlation. Qu et al. [3] studied liquid flow in an array of staggered square micro pin fins and also observed a stronger power law dependence of the Nusselt number on the Reynolds number. By comparing the experimental results with two previous heat transfer correlations for flow in micro pin fin arrays, Siu-Ho et al. [4] demonstrated the need for developing new predictive correlations that are specifically tailored to micro pin fin arrays.

Kosar et al. [5,6] studied and compared flow over five micro pin fin heat sinks of different spacing, arrangements, and shapes, and it was shown that densely populated pin fins with staggered arrangements resulted in higher heat transfer coefficients compared to large pin fin spacing and inline configurations. Moreover, micro pin fins with sharp pointed regions generated higher heat transfer coefficients than streamlined pin fins. Other experimental studies by Prasher [7] and Liu [8] as well as numerical studies by Koz et al. [9], Wang et al. [10], and Meis et al. [11] demonstrated that thermal and hydrodynamic characteristics of micro pin fin heat sinks are strongly affected by multiple factors, including the tip clearance, aspect ratio of the channels, end-wall effect, and the tip clearance, the geometrical shape, the density, and the array configuration of the pin fins. An optimization modeling study was completed by Tullius et al. [12] by considering four parameters-the tip clearance, the geometrical shapes, pin fin to channel height ratio, pin fin width and spacing, and pin fin material. Densely populated triangular pin fins with larger fin height and smaller fin width yield the best performance.

The above mentioned studies at the micro scale mainly concern array of pin fins. This is not the case at the macro scale. Montelpare and Ricci [13] experimentally examined heat transfer from a single heated pin fin (11 mm in diameter) with the aid of infrared thermography. They visualized the flow using ink tracers and related the thermal behavior with the flow field. Among the four shapes (circular, square, triangular, and rhomboidal) tested, triangular fin had the greatest heat transfer rate because the separation on the vertices of the triangular pin was strong, leading to a rigorous

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NOMENCLATURE

A_{heater}	surface area of the heater
D_h	hydraulic diameter of microchannel
f	Darcy friction factor
h	area-averaged convective heat transfer coefficient
k	thermal conductivity of the working fluid
L	heater length
$L_{entr,T}$	thermal entrance length
Ma	Mach number of working fluid
$\overline{Nu}$	area-averaged Nusselt number
Nu_{fd}	fully developed Nusselt number
Nu_{loc}	local Nusselt number
Pr	Prandtl number
$\dot{Q}_{heater}$	power rate supplied to the heater
$\dot{Q}_{loss}$	heat loss rate from heater other than convection directly to fluid
Re	Reynolds number based on channel hydraulic diameter
Re_D	Reynolds number based on pillar diameter
$\overline{T}$	area-averaged surface temperature
T_{in}	fluid inlet temperature
TKE	turbulent kinetic energy
$\overline{u}$	time-averaged velocity component along x direction
u	instantaneous velocity component along x direction
u'	instantaneous velocity fluctuation component along x direction
u'_{rms}	RMS of the velocity fluctuation component along x direction
$\overline{v}$	time-averaged velocity component along y direction
v	instantaneous velocity component along y direction
v'	instantaneous velocity fluctuation component along y direction
v'_{rms}	RMS of the velocity fluctuation component along y direction
V	average fluid inlet velocity
$\overline{\varpi}$	time-averaged vorticity

Greek symbols

ρ	density
μ	dynamic viscosity
ε	surface roughness

remixing in the wake behind the pin. To enhance heat transfer across a macro-scale circular cylinder, Eckert and Drake [14] placed a small rod on the stagnation line upstream of a heated cylinder. The rod, which functioned as a single pin fin in cross flow, stimulated disturbance. Up to 25% increase in heat transfer coefficient and 7% increase in free stream turbulence levels were reported. Tsutsui et al. [15,16] studied heat transfer enhancement of a small rod upstream of a square prism and a circular cylinder. Flow visualization showed that the cylinder's front face was exposed to the rod's wake, and heat transfer was enhanced by 40% at the optimum condition compared to a cylinder without an upstream rod.

The hydrodynamics of flow around a low aspect ratio cylinder has been studied both experimentally and numerically. Armellini et al. [17] experimentally investigated the flow structures around single cylinders of different shapes (square, circular, triangular, and rhomboidal) using 2D Particle Image Velocimetry (*PIV*). By detailed flow visualizations and analysis, they showed that the near wake downstream of the cylinders was influenced by vortical structures originated at the channel wall/obstacle junction. Also, an alternate vortex shedding or an irregular shedding mode was observed behind the cylinders depending on the Reynolds number. Numerical models by Mittal [18] and Huang et al. [19] simulated the flow past a cylinder to study end-wall effects, and it was found that the presence of walls suppressed the vortex shedding and substantially affected the shedding pattern. Kim et al. [20] modeled the turbulent flow past a square cylinder in a confined channel. They found that when a vortex shed from the cylinder approached one of the channel walls, it induced a counter-rotating vortex originating from the wall. This demonstrated that the cylinder in cross flow enhanced mixing.

Since many pin fin variables affect the heat transfer process, decoupling some of these parameters and studying a more rudimentary configuration, such as a solitary pin fin can help extend knowledge about the hydrodynamic and thermal processes in such flow configurations at the micro scale. The study of a single pin fin in microchannels is scarce, perhaps, because it is experimentally more challenging-unlike at the convectional scale-to obtain accurate measurements at the small scale.

To study the hydrodynamic mechanisms controlling the heat transfer process in micro pin fins entranced inside a microchannel, accurate local measurements of basic pin fin configurations were performed. These measurements decoupled the effect of the pin fin array and enabled fundamental measurements of flow around a single pin fin in a microchannel. The area-averaged heat transfer coefficient of air flow in a microchannel was measured. The effect of the pillar shape was studied on six micro-devices with different pillar configurations. Micro particle image velocimetry (μPIV) technique was used to observe flow structure downstream of a pillar; furthermore, a normalized parameter, turbulent kinetic energy (*TKE*) representing the intensity of velocity fluctuation, was defined, analyzed, and compared to the heat transfer trends.

2. Experimental apparatus and method

2.1. The micro-device

The micro device was fabricated from a Pyrex wafer anodically bonded to a silicon wafer and the schematic is shown in Fig. 1. For the six microchannel devices tested, each one contained a fluid channel (18.5 mm long, 1.5 mm wide, and 225 μm high). Fluid entered the channel, flowed across a pillar before been heated by a 100 nm thick, 1 mm × 1 mm serpentine heater, which is 225 μm away from the pillar's center (Fig. 1c). The fluid then left the channel through the exit manifold. Among the six devices, three devices had a single 150 μm diameter (or area equivalent) circular pillar, triangular pillar, and diamond pillar; one had a larger circular pillar with a diameter of 250 μm; one had two circular pillars in a row with a spacing of 200 μm; and one had no pillar (Table 1).

The fixture (Fig. 1a), precision machined from Delrin, was designed to contain the micro-devices and provide a fluid connection interface from an external fittings to the microchannel. To make electrical connection, two spring-loaded contact probes were fit into the fixture and protruded above a mating surface, contacting the two aluminum pads on the micro-devices. O-rings were used to achieve fluidic seals with the micro-devices. The devices were held in the fixture by a 4 mm thick aluminum cover plate.

2.2. Apparatus

To measure the heat transfer coefficient in the microchannel, an open flow loop (Fig. 2a) was constructed to supply the flow to the micro-device fixture. Compressed air passed through a needle