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Research Paper

Interferometric measurement and numerical comparisons of supersonic heat transfer flows in microchannel

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HIGHLIGHTS

- Effective cooling design by super-/sub-sonic air flow in microchannels is proposed.
- Microscale supersonic flows is successfully generated and examined.
- Microchannel flow density field were visualized quantitatively by interferometer.
- The bump design shows great potential of heat transfer enhancement in microscale.

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ABSTRACT

With the fast development of electronic systems and the ever-increasing demand of thermally "smart" design in space and aeronautic engineering, the heat transfer innovations and high heat flux challenges have become a hot topic for decades. This study is aimed at the effective cooling heat transfer design by super-/sub-sonic air flow in microscale channels for high heat flux devices. The design is based on the low temperature flows with supersonic expansion in microscale, which yields a compact and simple design. By careful microelectromechanical process, microscale straight and bumped channels (with simple arc curve) are fabricated and experimentally tested in this study. The microscale flow field and density distributions under new designs are visualized quantitatively by an advanced phase-shifting interferometer system, which results are then compared carefully with numerical simulations. In this study, large differences between the two designs in density distribution and temperature changes (around 50 K) are found. The high heat flux potential for supersonic microchannel flows is realized and discussion into detail. It is confirmed that the bump design contributes significantly to the heat transfer enhancement, which shows potential for future application in novel system designs.

1. Introduction

Microchannel fluid dynamics and heat transfer problems have become one of the hot topics in engineering fields, due to the wide application of microscale devices and the ever-increasing heating/cooling demands [1–3]. It is reported in recent years that the power density of new generation integrated circuits has increased to higher than 1.0 MW/m^2 [1]. The fast heating/cooling and thermal control process in aeronautics have also put forward new challenges, which require both miniaturized (and compact) design and high heat flux capacities [4,5]. In order to solve that problem, many researchers have been focused on the microfluidics related analysis, such as the thermal resistance examination, superconducting, heat transfer fluids, novel designs in microscales [5,6], etc.

However, it is still difficult to meet the high standard demand, as the microscale flow and heat transfer potentials are yet to be improved. For the enhancement of heat transfer behaviors, and mainly for cooling performance, large numbers of studies have been published in open literature. The focus on microchannel flows is one major proposal due to its relatively higher performance and the easy application for mini- and micro- sized devices. For single-phase flows, several representative studies [4–9] have experimentally and partial-numerically revealed the basic performance of circular and rectangular microchannels and their integration for cooling devices. Also, many working fluids, such as gas flow of

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Nomenclature

A	area
E	energy
f	friction factor
h	height, enthalpy
I	unit tensor
k	thermal conductivity
K	Gladstone-Dale constant
l	optical length
L	length
n	refractive index
N	fringe number
p	pressure
R	gas constant
t	time
T	temperature
v	velocity
X	x direction
Y	y direction

Greek symbols

λ	wave length
ρ	density
μ	viscosity coefficient
λ	wavelength
τ	stress tensor

Subscripts

0	test/reference value, initial value
in	inlet
out	outlet
t	time dependent value
r	reference value
eff	effective value

incompressible and compressible designs, microchannel geometry modifications, as well as nano-fluid flow systems, have been conducted to test the microscale heat transfer performances [10–14]. In the study of Wang and his colleagues [10,14], the microchannel through flows with top-truncated double-layers are numerically discussed, and an inverse method are further developed for optimization later. Their design showed generally 24%–40% reduction of thermal resistance in the numerical simulations, which is promising for future real application development. However, the main designs are still largely dependent on the pumping power range for those studies. It is found that high pressure or multiphase flows generally yield higher performance, but it still diverges from case to case (and depend on specific designs) [15–18]. Recently, in a novel microscale heat transfer design with supercritical fluids [19–21] has also been conducted and it indicates that the fluid choice and channel design/control are both important factors for improving heat transfer performance. From those existing studies, limitations are seen for both forced kind of heat transfer design and natural convection kinds. If the target is to achieve high heat flux around 1.0 MW/m^2, much higher refrigerant flow rate or phase change rate are necessary [1–3,22]. Also the microscale fabrication and detailed system design and thermal efficiency analysis still remain as problems yet to be solved [23,24]. New proposals for the microscale fluidic designs to improve the heat transfer and flow control are still needed in this field.

The current study is focused on a new design of utilizing supersonic flow into microscale heat transfer apparatus. The supersonic flow can be generated by adiabatic expansion, and it generates shock wave and lower temperature downstream flow condition in the microscale [25–28]. In this study, a newly proposed microchannel with simple bump sections, as a convergent-divergent section, is experimentally fabricated and tested as a candidate for the high heat flux cooling device. By generating supersonic flow, low-temperature downstream region can be realized for possible heat transfer section. Fundamental investigations of supersonic fluid flow realization and microchannel design have been made in previous trials [29,30]. However, only the general heat transfer boundary or heat transfer effects on the flow (i.e., the flow dynamics) have been discussed in literature. To utilize the low temperature flow potential, the basic supersonic flow in microscale can be proposed in this study for heat transfer goals.

And in this study, it is set as a goal to visualize the detailed density behaviors and temperature evolutions in the newly designed supersonic microchannel. he temperature distribution is important to evaluate the heat transfer performance between the flow and walls, i.e., cooling performance of the heat sink in microscale. However, it is seen as a very difficult task to visualize the flow and density/temperature field inside microchannel. In literature, very few experimental studies of the microchannel flow visualization of the flow and density field can be found [30,31]. In this study, for a feasibility comparison, a newly designed phase-shifting Mach-Zehnder interferometer system is also utilized as a non-intrusive and quantitative measurement technique [31,32]. Generally, it is difficult to measure the flow inside the microchannel as the optical length difference and refractive index measurement is inadequate for well data manipulation. The interferometer system is proposed in this study to visualize the basic density changes inside the microchannel to test the supersonic flow heat transfer and compare with the numerical simulation results.

The overall objective of this study is to confirm the availability of the bumped channel for the micro heat sink, and to measure the density distributions of supersonic flow inside the microchannel using a phase-sifting interferometer. The following sections will first show the design, the fabrication of the new heat transfer channel, and then a newly proposed interferometric measurement system is introduced. After that the experimental results are compared with numerical simulation data for basic density field and heat transfer analysis. Other details of heat transfer characteristics, comparisons between straight channel and newly designed bump channels, and the effects of supersonic flow designs are also discussed into detail in this study.

2. Microchannel design and interferometer measurement system

2.1. Microchannel design and fabrication

In order to evaluate the effect of the micro-nozzle on the density distributions, two types of the microchannel were designed. One has a straight channel shown in Fig. 1(a). The other one has a micro-nozzle at the inlet region of the channel as shown in Fig. 1(b), which was named as bumped nozzle. The shape of the bumped nozzle follows a simple arc curve that was easy for fabrication. The advantages of bumped nozzle were also discussed in previous studies [29,30]. Silicon plate was sandwiched between two TEMPAX© plates by anodic bonding for visualization in this design. The main target of the current design is to test and compare the heat transfer flow between the newly designed bump channel and conventional straight channels. The detailed size and chamber flow system can also be found in Fig. 1(a) and (b). For the real