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Thermohydraulic performance of microchannel heat sinks with triangular ribs on sidewalls – Part 2: Average fluid flow and heat transfer characteristics

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ABSTRACT

Triangular ribs mounted in the microchannel heat sink generally result in higher heat transfer coefficient, but are usually accompanied by higher pressure drop per unit length. In order to obtain some insight into the effect of geometry parameters of triangular ribs on laminar flow and heat transfer characteristics, three-dimensional conjugated heat transfer models taking account of the entrance effect, viscous heating and temperature-dependent thermophysical properties are conducted, and four non-dimensional variables related to the width, height, converging-diverging ratio and spacing of the triangular rib for both aligned and offset arrangements are designed. Effects of the geometry and arrangement of triangular ribs on thermohydraulic performance are examined by the variations of average friction factor and Nusselt number for Reynolds number (Re) ranging from 187 to 715. The studied microchannels have the same width (W_c) of 0.1 mm and same depth (H_c) of 0.2 mm in the constant cross-section region. The geometric parameters of aligned or offset triangular ribs are ranged in 0.025–0.4 mm for width (W_r), 0.005–0.025 mm for height (H_r), 0.2–5 mm for spacing (S_r) and 0–1 for the width ratio of converging region to a single rib (W_{con}/W_r). Based on the total 660 computational cases of the microchannel heat sinks with triangular ribs, the correlations of average friction factor and Nusselt number are proposed, respectively for aligned and offset arrangements. For the studied Reynolds number range and geometry parameters of flow passage, the microchannel heat sinks with aligned triangular ribs present 1.03–2.01 times higher of average Nusselt number and 1.06–9.09 times larger of average friction factor, and those with offset triangular ribs show 1.01–2.16 times higher of average Nusselt number and 1.04–7.43 times larger of average friction factor, compared with the reference straight microchannel heat sink. Proposed heat transfer and friction factor correlations show good agreements with the computational results for the microchannel heat sinks within the parameter ranges of $187 \le Re \le 715$, $0.25 \le W_r/W_c \le 4$, $0.05 \le H_r/W_c \le 0.25$, $0 \le W_{con}/W_r \le 1$, and $2 \le S_r/W_c \le 50$.

1. Introduction

Since the pioneering work by Tuckerman and Pease [1] in the early 1980s, the microchannel heat sink incorporating single-phase liquid flow has been successfully used for heat removal in a variety of devices, such as the cooling of electronic devices, automotive heat exchangers, laser process equipment and aerospace technology. The small size and its ability to dissipate heat generated by modern electronics make them the preferred choice for the electronic cooling systems. However, with the advancement in micro and nano electronics technology, the requirement of heat flux dissipation rate is reaching 1 kW·cm^{-2}, which imposes limit on product design with traditional straight microchannel heat sink and requires advanced manufacturing technique and heat sink design with further higher heat removal capability [2–4]. In an attempt to improve overall thermal performance, different microchannel geometries with the potential to deliver high-heat flux rates have been proposed in recent years.

Xu et al. [5,6] demonstrated the interrupted microchannel heat sink which consisted of a set of separated zones adjoining shortened parallel microchannels and transverse microchambers, Chai et al. [7–9] and Wong and Lee [10] introduced the staggered ribs into the transverse microchambers for further heat transfer

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Nomenclature

A	area, m^2
c_p	specific heat, J·kg^{-1}·K^{-1}
D_h	hydraulic diameter, m
$\bar{f}$	average friction factor
h	heat transfer coefficient, W·m^{-2}·K^{-1}
$\bar{h}$	average heat transfer coefficient, W·m^{-2}·K^{-1}
H	height, m
k	thermal conductivity, W·m^{-1}·K^{-1}
L	length, m
Nu	Nusselt number
$\overline{Nu}$	average Nusselt number
p	pressure, Pa
q	heat flux, W·m^{-2}
Re	Reynolds number
S	spacing, m
T	temperature, K
$\bar{T}$	average temperature, K
u	velocity, m·s^{-1}
$\bar{u}$	average velocity, m·s^{-1}
W	width, m
x,y,z	three coordinates shown in Fig. 1a, m

Greek letters

ρ	density, kg·m^{-3}
μ	dynamic viscosity, Pa·s

Subscripts

c	channel
com	computational domain
con	contraction
exp	experimental
in	inlet
f	fluid
out	outlet
r	rib
s	silicon
w	heat sink base

Abbreviations

ATR	aligned triangular ribs
CFD	computational fluid dynamics
MCHS	microchannel heat sink
OTR	offset triangular ribs

augmentation and investigated the influence of rib geometry on heat transfer performance, Cao and Xu [11] suspended the consecutive conical-mesh inserts in channels to modulate flow and temperature fields. Promvonge et al. [12], Liu et al. [13], Ebrahimi et al. [14], Foong et al. [15] and Xie et al. [16] developed the microchannel heat sinks with passive microstructures inside, such as baffles, longitudinal vortex generators, internal longitudinal fins and internal bifurcations, and studied their fluid flow and heat transfer characteristics. Sui et al. [17,18], Mohammed et al. [19] and Lin et al. [20] investigated the thermal performance of wavy microchannel heat sink with different geometry parameters, such as channel width, wall width, cross section aspect ratio and relative wavy amplitude, and Ghaedamini et al. [21] studied the developing forced convection in the converging–diverging microchannel heat sink. Chai et al. [22–29] and Beng and Japar [30] proposed several microchannel heat sink with different ribs and cavities on sidewalls and studied their thermohydraulic performance, and Xia et al. [31–33] and Ghani et al. [34,35] introduced the ribs into the microchannel with cavities to further improve the heat transfer performance. Table 1 provides a brief summary of these studies, which depicts the flow condition, channel geometry and main findings.

Generally, the principles of enhanced heat transfer can be attributed to one or several of the following mechanisms, including the interruption of boundary layer formation, the enhanced convective fluid mixing, and the increased heat transfer surface area. However, the heat transfer augmentation methods usually lead to higher pressure drop penalty, and the application of such microchannel to electronics cooling imposes severe design constraints on the system design. For a given heat dissipation rate, the flow rate, pressure drop, fluid temperature rise, and fluid inlet to surface temperature difference requirements necessitate optimization of the channel geometry [36]. Further, as indicated in Table 1, for each type of microchannel heat sink, the geometry parameters of enhancement element in the form of rib, cavity, baffle, bifurcation and fin have a significant influence on the fluid low and heat transfer characteristics, which need more accurate data for the deep investigation of heat transfer process.

For the microchannel heat sink with aligned or offset ribs on sidewalls, Chai et al. [26] has conducted three-dimensional numerical models with five different shapes of offset ribs to examine the local and average friction factor and Nusselt number, and further for a systematic and detailed analysis, Chai et al. [27–29] concentrated on the fan-shaped ribs and investigated the influence of rib geometry and arrangement on thermal and hydraulic characteristics of such microchannel heat sink. As a continuous study, we presently focus on the triangular ribs mounted in microchannels with either aligned or offset arrangements. The first part of this two-part study has supplied the basic fluid flow and heat transfer mechanism in such microchannel heat sink and identified the effects of the geometric and arrangement parameters on local fluid flow and heat transfer characteristics [37]. However, to design new microchannel heat sinks and evaluate their thermohydraulic performance, more accurate information on friction factor and heat transfer coefficient are required as a function of operation conditions and geometric parameters. Consequently, this second part emphasizes the effects of triangular rib geometry and arrangement on the average thermohydraulic performance in wide ranges of operation conditions and geometry and arrangement parameters. Altogether 660 computational cases have been conducted to investigate the effects of the geometric parameters on the thermohydraulic characteristics of the microchannel heat sinks with triangular ribs for Reynolds number ranging from 187 to 715. As a result, the friction factor and Nusselt number correlations for microchannel heat sinks with triangular ribs are developed as a function of operation conditions and geometric parameters.

2. Computational method

2.1. Conservation equations

A three-dimensional solid-fluid conjugate model is used to predict heat transfer performance for such microchannel heat sink with the following assumptions: developing flow, steady and laminar flow, varied fluid thermophysical properties and considering viscous dissipation. The continuity, momentum and energy equations for the problem can be written as