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Fluid flow and heat transfer investigations on enhanced microchannel heat sink using oblique fins with parametric study

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ABSTRACT

Enhanced microchannel heat sink with sectional oblique fin is used to modulate the flow in contrast to continuous straight fin. The re-initialization of thermal boundary layer at the leading edge of each oblique due to breakage of continuous fin into oblique sections and the secondary flow due to these oblique cuts resulted in better heat transfer and a comparable pressure drop. Extensive experimental investigations are carried out with silicon test vehicle with hydraulic diameter of 100 μm and 200 μm and de-ionized water as flowing fluid. A parametric study involving the oblique angle, fin pitch is also carried out. Appreciable heat transfer augmentation is also achieved with maximum heat transfer performance enhancement at 47% when Re = 680. Comparable pressure drop to conventional microchannel is maintained up to Re = 500. Parametric study suggests that smaller oblique angle and smaller fin pitch are beneficial for heat transfer enhancement. The performance of the microchannel with 100 μm channel width and 27° oblique angle is found to be optimum.

1. Introduction

The advancement in packaging technology has led to smaller chip size associated with higher and more concentrated heat flux. With smaller chip size and high heat flux comes the generation of high temperature with addition of hot spots which can accelerate the meantime to failure (MTTF) and reduce the lifespan of electronic devices as described by Black's equation [1]. Therefore, cooling of electronic devices is a persistent challenge in package design. Heat sinks with mini/microchannel are currently most widely used for the cooling of small but highly heated electronic devices, due to their advantages such as compactness, light weight and higher heat transfer surface area to fluid volume ratio compared with other macro-scale systems. Since the concept of microchannel heat sink was first proposed by Tuckerman and Pease [2] in 1981, numerous studies has been conducted to investigate its flow and heat transfer characteristic in microchannels. The study of Copeland et al. [3] revealed the application difficulties for the conventional microchannel, which were associated with high pressure drop and significant lateral temperature gradient. However, the report of Prasher and Chang [4] that single phase microchannel liquid cooling was capable of cooling heat flux as high as 1250 W/cm^2, still holds great promise of microchannels as a viable cooling option for microelectronics cooling.

Extensive research on techniques to enhance the heat transfer performance of microchannel heat sinks has been conducted over the past decades. Based on the minimization of the flow resistance between a volume (volumetric heater) and a point (cooling liquid stream), a tree-shaped channel network was proposed by Bejan and Errera [5]. Chen and Cheng [6] proposed a right-angled bifurcation in a rectangular shaped heat sink while Pence [7] preferred a smaller bifurcation angle in a disk shaped heat sink. Both designs deployed self-similar fractal-like branches in a heat sink at a fixed ratio between the upstream and downstream channel width and channel length, leading to identical bifurcating pattern at each level. On the other hand, the concept of deploying re-entrant space in microchannel heat sink was explored experimentally and numerically by Xu et al. [8–9]. Their studies indicated that the thinning of boundary layers after every re-entrant space resulted local heat transfer enhancement and similar or reduced pressure drop across the enhanced heat sink compared to that of the conventional configuration. Lee et al. [10] proposed a hot spot mitigation scheme by creating a recess at the cover lid just before hot spot region.

As an effective method to promote better fluid mixing, secondary flow has been listed as one of the efficient heat transfer augmentation techniques. Steinke and Kandlikar [11] suggested two potential methods in generating secondary flow for microchannel application.

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Nomenclature

A	convection heat transfer area, m^2
A_c	fin area, m^2
D_h	hydraulic diameter, m
H	channel height, μm
K	loss coefficient
L	heat sink length, mm
L'	characteristic length
N	number of fin
Nu	Nusselt number
P	fin perimeter, m
PP	pump power, W
ΔP	pressure drop, Pa
Pr	Prandtl number
Q	volumetric flow rate, m^3/s
R	thermal resistance, °C/W
R_s	summation of spreading resistance and 1D conduction resistance, °C/W
Re	Reynolds number
T	temperature, °C
W	heat sink width, mm
X, Y, Z	global coordinate system
X'	dimensionless axial distance, $X' = X/L$
Y'	dimensionless channel height, $Y' = Y/H$
Z'	dimensionless heat sink width, $Z' = Z/W$
c_p	specific heat capacity, kJ/kgK
f	friction factor
h	heat transfer coefficient, W/m^{2}K
k	thermal conductivity, W/mK
l	fin length, μm
$\dot{m}$	mass flow rate, kg/s
n	number of fin row
p	fin pitch, μm
q	heat transfer rate, W
q^*	heat transfer rate per unit heater, W
q''	heat flux, W/m^2
u	velocity, m/s
w	width, μm

Greek symbols

α	aspect ratio
θ	oblique angle, °
Δ	gradient
μ	dynamic viscosity, Ns/m^2
ρ	mass density, kg/m^3

Subscripts

ave	average
b	base (unfinned)
c	contraction
ch	channel
CM	conventional microchannel
conv	convective
EM	enhanced microchannel
e	expansion
f	fluid
fin	fin
HS	heat sink
in	inlet
max	maximum
ob	oblique channel
out	outlet
p	plenum
si	silicon
sp	spreading
tot	total
w	wall

The first suggestion was to add smaller channels at a certain angle between two main liquid channels. Alternatively, secondary flow can also be generated by a venturi effect. Both methods can lead to heat transfer enhancement phenomenon without or with slight additional pumping power consumption. This technique can be applied by various kinds of fins and plates arrangement. The study of Tatsumi et al. [12] on parallel plate fin arrays with oblique notches suggested that the presence of oblique notches resulted in heat transfer enhancement through interrupting thermal boundary layers and promoting the generation of spanwise flow (secondary flow).

The concept of oblique fins in microchannel heat sinks was proposed by Lee et al. [13] By breaking the continuous fins into oblique sections, significant local and global heat transfer enhanced was achievable with little or negligible pressure drop penalty. Fan et al. [14] introduced the concept of oblique fins into the design of cylindrical heat sinks and obtained a much larger average Nusselt number compared with that of conventional straight fin heat sink. Detailed numerical and experimental studies were subsequently performed by Lee et al. [15] to further look into the hydrodynamics and thermal development along the oblique finned microchannel heat sink, providing some insights to the fundamental mechanism of this technology. These all works focus on overall flow and heat transfer in oblique fin channel. Since the change in flow and heat transfer behavior in oblique fin can be attributed to local geometry change such as oblique fin and oblique channel, it will be interesting to see the local flow and heat transfer behavior. Dimension is another important aspect of the oblique fin channel which can affect the flow and heat transfer. In a recent review article, it has been observed by Kandlikar et al. [16] that the heat transfer coefficients of these oblique finned copper microchannels were relatively low due to large hydraulic diameters and suggested it will be interesting to see performance at smaller level. In addition, there are a few key design parameters that greatly influence the heat transfer and pressure drop performance in oblique finned microchannels. Therefore, a parametric study is essential to explore the outcome of varying these parameters.

The present work tries to address these challenges by experimentally investigating the oblique fin microchannels of 100 micron and 200 micron nominal width. The local flow and heat transfer behavior is observed and analyzed. A parametric study looking into the effect of oblique angles and fin pitch is carried out. At last, an optimum geometry is suggested based on the results.

2. Experimental setup

A schematic of the experimental flow loop is shown in Fig. 1. Deionized water from a reservoir tank is driven through the flow loop using a micro-annular gear pump. This pump forces the coolant through a 15 μm filter and a flow meter before entering the microchannel test section. A heat exchanger (connected to water bath) is used to regulate the water temperature before coolant enters the test section. Pressure transmitters are attached to the