International Journal of Thermal Sciences 76 (2014) 1–10

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Experimental investigation on heat transfer and pressure drop of a novel cylindrical oblique fin heat sink

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ARTICLE INFO

Article history:
Received 30 January 2013
Received in revised form
12 August 2013
Accepted 16 August 2013
Available online 27 September 2013

Keywords:
Cylindrical oblique fin heat sink
Secondary channel
Edge effect
Heat transfer
Pressure drop

ABSTRACT

A novel cylindrical oblique fin minichannel heat sink, in the form of an enveloping jacket, was proposed to be fitted over cylindrical heat sources. The presence of the oblique fins disrupts and reinitializes the boundary layer development at the leading edge of each fin. This results in a significant reduction of the boundary layer thickness and causes the flow to remain in the developing state. Experimental investigations were conducted to compare its heat transfer performance with conventional straight fin minichannel heat sink. The test pieces were fabricated from copper and measurements on the heat transfer characteristics were performed for Reynolds number ranging from 50 to 500. In addition, the effects of flow distribution were examined and it was found that cylindrical oblique fin structure eliminates the edge effect which is present in the planar oblique fin configuration. The uniform secondary flow generated by the cylindrical oblique fin structure improves fluid mixing and enhances heat transfer significantly. The experimental results showed that the average Nusselt number for the cylindrical oblique fin minichannel heat sink increases up to 75.6% and the total thermal resistance decreases up to 59.1% compared to the conventional straight fin heat sink. For a heat flux of 6.1 W/cm^2 and Reynolds number of 300, the average surface temperature of cylindrical heat sink is reduced by 4.3 °C compared to conventional straight fin heat sink while the required pumping power remains comparable.

1. Introduction

The ever increasing cooling demand for various applications such as microprocessors, batteries, etc. has challenged the researchers to come up with innovative and effective cooling techniques that ensure optimal performance and improved reliability. Conventional cooling methods like air cooling are unable to keep up with the cooling demands while advanced cooling techniques like two-phase cooling can dissipate large heat fluxes on the order of tens of MW/m^2. However, such techniques typically come with tradeoffs like having more complex system and more prone to flow instabilities. Single-phase micro/mini-cooling is a promising solution offering several advantages such as ease of implementation, compactness, light weight and higher heat transfer surface area to fluid volume ratio. The concept of microchannel heat sink was first introduced by Tuckerman and Pease [1] in 1981. The microchannels fabricated in silicon chips which had channel dimensions of 50 μm (channel width w_c) × 302 μm (channel depth z), were able to dissipate heat flux of up to 790 W/cm^2 while maintaining a maximum temperature difference between the substrate and inlet water of 71 °C. However, the pressure drops in these microchannels were very high, at 200 kPa for plain microchannels and 380 kPa for pin fin microchannels. Similarly, Prasher and Chang [2] reported that single phase microchannel liquid cooling was capable of cooling heat flux as high as 1250 W/cm^2 at the expense of a high pressure drop of 50 kPa.

Lee et al. [3] conducted experimental investigations to explore the validity of classical correlations based on the conventional sized channels for predicting the thermal behavior in single-phase flow through rectangular microchannels. The numerical results were found to be in good agreement with the experimental data, suggesting that such approaches, when coupled with carefully matched entrance and boundary conditions, can be employed with confidence for predicting heat transfer behavior in microchannels in the dimensional range. Liu and Garimella [4] also presented five approximate analytical models for predicting the convective heat transfer in microchannel heat sinks using computational fluid dynamics models. These approaches include the simulation from a 1D

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http://dx.doi.org/10.1016/j.ijthermalsci.2013.08.007

Nomenclature

A	heat transfer surface area, mm^2
D_h	hydraulic diameter, mm
D	heat source diameter, mm
H	channel height, mm
I	current, A
K	loss coefficient
L	heat sink length, mm
N	number of channels
Nu	Nusselt number
ΔP	pressure drop, Pa
Q	volumetric flow rate, L/min
Re	Reynolds number
R	thermal resistance, °C/W
T	temperature, °C
U	voltage, V
X, Y, Z	nondimensional Cartesian coordinates
c_p	specific heat capacity, KJ/kg K
h	heat transfer coefficient, W/m^2 K
k	thermal conductivity, W/m K
p	perimeter, mm
q	heat gain by the fluid, W
x, y, z	Cartesian coordinates
v	average fluid velocity, m/s
W	main channel bottom width, mm

Greek symbols

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

Subscript

ave	average
ch	channel
f	fluid
cu	copper
c	contraction
e	expansion
in	inlet
o	outlet
m	mean bulk fluid
tot	total
w	wall
eq	equivalent

resistance model, a fin approach, two fin-liquid coupled models, and a porous medium approach. A modified thermal boundary condition was proposed to characterize the heat flux distribution in the analytical model. Tao et al. [5] presented three possible mechanisms for the single-phase heat transfer enhancement, namely the decrease of the thermal boundary layer, the increase of flow interruptions, and the increase of the velocity gradient near the heated surface. Based on these mechanisms, various microchannels heat sinks designs were proposed to enhance heat transfer performance. A tree shaped channel heat sink was proposed by Bejan and Errera [6], which was based on the construct theory to minimize the flow resistance between a volume and a point. Sui et al. [7] studied the wavy microchannels with rectangular cross section based on CFD simulations. It was found that Dean Vortices were generated when liquid coolant was flown through the wavy microchannel. As a result, significant heat transfer enhancement with a much smaller pressure drop penalty was achieved when compared with straight microchannels configuration. Different shapes of the cross-sectional area of the microchannels were shown to affect cooling performance. For example, Nonino et al. [8] investigated on microchannels with different cross-sectional shapes for their flow behavior and wall heat flux while Sadeghi et al. [9] examined a laminar forced convection channel with an annular cross section while maintaining a uniform temperature at the inner wall and an adiabatic outer wall. Many other researchers [10–14] also used numerical methods to study heat transfer enhancement mainly on the developed flow behavior in microchannels.

Micro/mini channel geometries can be designed to generate secondary flow that enhances heat transfer. This technique can be applied by incorporating offset strip fins, chevron plates and other similar geometries. Steinke and Kandlikar [10] suggested placing smaller secondary channels at an angle between the main channels for microchannel application. Secondary flow moved from one channel to another through these channels. A venturi can be also used to produce secondary flow without external power. This technique increased fluid mixing and the addition of another flow stream to the main flow stream eliminated the need for secondary flow pumping power. Colgan et al. [11] presented detailed experimental results comparing various offset in fin geometries. They showed that the 75 or 100 μm pitch silicon microchannel cooler with staggered fins can achieve excellent heat transfer performance at a very high power level. In a recent study by Lee et al. [12], oblique fin microchannel was proposed by creating smaller branching channels through cutting obliquely along the straight fins on the planar surface. This structure was shown to enhance heat transfer performance significantly with negligible pressure drop penalty.

For single phase cooling technology, most studies focused on cooling planar surfaces with the fluid flowing through fins from the entrance to the exit of the channel [1–3,6–9,13–15]. The present literature for cooling heat sources with cylindrical surface such as high powered LED, high powered laser, motors, high capacity battery etc., is rather scarce [16,17]. In this paper, a novel cylindrical oblique fin minichannel in the form of an enveloping jacket was proposed to be fitted over cylindrical heat sources. Experimental investigations were conducted to study its heat transfer performance in both conventional and cylindrical oblique fin minichannel heat sinks. The test pieces were fabricated from copper and measurements on the heat transfer characteristics were performed for Reynolds number ranging from 50 to 500. The edge effect for oblique fin minichannel heat sink was then discussed and experiments were conducted to verify its effect on heat transfer.

2. Theory

The proposed design in Fig. 1 consists of two types of channel arrays, main flow channels and oblique secondary channels. The main flow channels are aligned with the axial direction while the oblique secondary channels are branched out from the main flow channel at an oblique angle. The presence of the oblique secondary channels disrupts and reinitializes the boundary layer development periodically. This results in the significant reduction of the boundary layer thickness and causes the flow to remain in the developing state unlike the conventional straight fin configuration. Therefore, the wall temperature gradient is consistently