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Constructal design of combined microchannel and micro pin fins for electronic cooling

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ABSTRACT

This paper presents a three-dimensional numerical study of steady, laminar, incompressible flow and forced convection heat transfer through a microchannel heat sink with micro pin fin inserts for both fixed and variable axial lengths. The objective of the study was to optimise the geometric configuration of an integrated microchannel and micro pin fins for different solid volumes so that the peak temperature in the configuration was minimised. The effect of the micro pin fins on the optimised microchannel was also investigated. The geometric optimisation of the integrated microchannel and micro pin fin was carried out using a computational fluid dynamics (CFD) code with a goal-driven optimisation tool subject to global constraints. The optimisation procedure was carried out in two steps. Firstly, the microchannel configuration was optimised without the micro pin fins inserted and the results were compared with similar work found in the open literature. This optimisation was carried out for both fixed and relaxed lengths. Thereafter, the integrated design of the microchannel and micro pin fins was optimised. The effect of the Bejan number on the solid volume fraction, channel aspect ratio and hydraulic diameter, pin fin aspect ratio, minimised peak temperature and maximised thermal conductance were reported.

Results showed that as the Bejan number increased, the minimised peak temperature decreased. Also, the maximum thermal conductance increased with the optimised microchannel structure with three to six rows of micro pin fin inserts. Diminishing return set in when the number of rows of micro pin fin inserts was greater than three for the fixed length but for the relaxed length, as the number of rows increased, the results improved but when it exceeded six diminishing returns set in for a fixed solid volume of 0.9 mm^3. For each Bejan number used in this study, there was an optimum channel hydraulic diameter and aspect ratio, solid volume fraction and pin fin aspect ratio that satisfied the global objective.

1. Introduction

Almost all literature acknowledges that the approach of utilising microchannel heat sinks to remove high heat fluxes in microelectromechanical systems (MEMS) was first presented by Tuckerman and Pease [1]. Since then, many analytical, experimental and numerical investigations have been carried out on microchannel and micro pin fin heat sinks especially in the area of geometric optimisation using different optimisation tools. Some of these works are mentioned below.

Knight et al. [2] used an analytical technique to optimise heat sinks with application to microchannel and their results showed 10–35% improvement in the thermal resistance over those presented by Tuckerman and Pease [1] and two other previous investigations. Other analytical investigations with optimisation with application to electronic cooling were carried out by Perret et al. [3], Murakami and Mikic [4] and Upadhye and Kandlikar [5].

Numerical investigations were carried out by Ryu et al. [6], [7] on microchannel heat sinks using the finite volume method incorporating an optimisation scheme which used the random search technique. Muller and Frechette [8] also used a numerical optimisation tool to optimise forced convection in microchannel heat sinks for minimum pumping power at high heat fluxes. The optimal fin configuration was found using the Newton method.

A detailed numerical simulation of the heat transfer occurring in a silicon-based micro-channel heat sink with optimisation of the geometric structure using a simplified three-dimensional conjugate heat transfer model (2D fluid flow and 3D heat transfer) was carried out by Li and Peterson [9,10]. Ndao et al. [11] carried out a multi-objective thermal design optimisation and comparative study of different electronic cooling technologies, which included microchannels, circular pin fins, offset strip fins and jet impingement using MATLAB's multi-objective algorithm functions to determine the optimal thermal design of each technology.

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Nomenclature

A	area (m^2)
Be	Bejan number
C	global thermal conductance
C_p	heat capacity (J/K)
D_h	channel hydraulic diameter (m)
D_f	pin–fin diameter (m)
H_c	channel height (m)
H_f	pin–fin height (m)
k_s	thermal conductivity of solid wall (W/mK)
k_f	thermal conductivity of fluid (W/mK)
M	height of computational volume (m)
N	length (m)
P	pressure (Pa)
q	heat transfer rate (W)
q''	heat flux (W/m^2)
R_{th}	thermal resistance (K/W), $\left(R_{th} = \frac{T_{fin}-T_{air}}{q}\right)$
s	pin–fin spacing (m)
T	temperature (°C)
t_1	half-width thickness of vertical solid (m)
t_2	channel base thickness (m)
t_3	channel base to height distance (m)
u,v,w	velocities in the x-, y- and z-directions (m/s)
V	computational domain volume (m^3)
V_f	volume of micro pin–fin (m^3)
W	computational domain width (m)
W_c	channel width (m)
W_t	total width of solid volume (m)

Greek symbols

Δ	difference
ρ	density (kg/m^3)
μ	dynamic viscosity (kg/m s)
α	thermal diffusivity (m^2/s)
ϕ	volume fraction

Subscripts

atm	atmosphere
f	fluid
max	maximum
min	minimum
opt	optimum
out	outlet
solid	solid
1–6	number of rows of pin fins

Husain and Kim [12] also carried out a numerical investigation of 3D fluid flow and heat transfer in a rectangular microchannel using water as a cooling fluid in a silicon substrate. Commercial code CFX 5.7 was used to formulate the numerical model while three surrogate models were applied to predict the optimal design point that minimises thermal resistance.

A more recent approach applied to studies carried out to investigate forced convection heat transfer in microchannel heat sinks is a geometric optimisation technique involving constraint specification. This approach is based on the constructal theory, which begins with the global objective(s) and the global constraint(s) of the flow system, and the fact that in the beginning, the geometry of the flow is missing [15]. This approach was also used in the geometric optimisation of pin fins [16–19].

Bello-Ochende et al. [13] and Ighalo [14] observed that in literature, in order to achieve optimal designs of microchannel heat sinks using CFD, optimisation was carried out using trial-and-error simulations. They proposed a design methodology which combined CFD with a mathematical optimisation algorithm (a leapfrog optimisation program and DYNAMIC-Q algorithm), which automated the optimisation process. Their results were compared with that obtained by Bello-Ochende et al. [16] which used the trial-and-error method. Ighalo [14] also used this method to optimise two and three rows of pin fins.

From the observation of Bello-Ochende et al. [13], this present work is aimed at optimising a rectangular microchannel heat sink embedded with micro pin fins using the goal-driven optimisation tool in the ANSYS workbench, which is an automated process. The advantage of this optimisation tool is that the geometry, meshing, simulation and the optimisation are carried out in the ANSYS workbench unlike the method previously used [13], where they had to couple the mathematical optimisation algorithm to FLUENT 6. In this work, a fixed volume constraint is applied to obtain global optima with respect to the channel aspect ratio, solid volume fraction, channel hydraulic diameter, pin–fin aspect ratio and Bejan number. The optimisation of the integrated microchannel and micro pin–fin heat sink will be based on minimising the peak temperature of the highly conductive silicon substrate into which they are inserted for fixed and variable lengths.

2. Model description

A physical model of a microchannel embedded inside a high-conducting solid which is the same used in the investigation carried out by Bello-Ochende et al. [13], is shown in Fig. 1. Fig. 2a and b shows the elemental volume of the microchannel heat sink inserted with micro pin fins used as the computational domain in this study. The length N, height M and width W of the solid are fixed, which makes the volume V fixed while t_1, t_2, t_3, H_c and W_c are varied but also subject to manufacturing constraints. The solid volume fraction or porosity ϕ is defined as the ratio of the solid volume to the total volume of the heat sink, which is only dependent on the cross-sectional area of the heat sink as shown in Eq. (1).

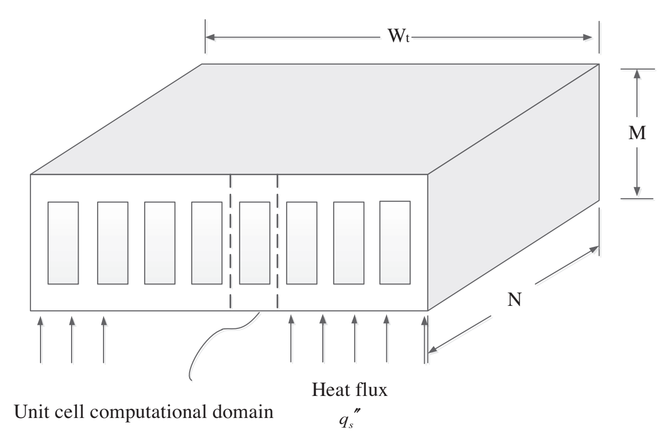

Fig. 1. (a) Physical model of a microchannel heat sink.