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Numerical investigation for optimizing segmented micro-channel heat sink by Taguchi-Grey method

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HIGHLIGHTS

- Novel segmented micro-channel heat sink has been designed.
- CFD models have been developed to simulate the performance of the segmented micro-channel.
- Enhanced the cooling performance of the straight micro-channel.
- Optimizing the segmented micro-channel using Taguchi-Grey method.
- Optimized design parameters for segmented micro-channel have been identified.

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ABSTRACT

The scale-down trend increases the chips' density and the high power handling capability generates unnecessary heat which can disrupt the reliability of the electronic devices. Therefore, various types of cooling solution have been proposed to enhance heat dissipation from the electronic devices. One of the solution is using inexpensive straight-channel heat sink. However, the presence of large temperature gradient between the upstream and downstream in the straight-channel can shorten the life span of the device and subsequently reduce the reliability. In this study, a novel segmented micro-channel is introduced to improve the thermal performance of the straight-channel heat sink. Computational fluid dynamic analysis are performed to investigate the performance of the micro-channel heat sink. The bottom of the heat sink is subjected to a constant heat flux condition and water is used as a coolant. Following that, Taguchi-grey method is applied to optimize the design of the segmented micro-channel. The effect of fin width, fin length, fin transverse distance, number of segments, channel width and mass flow rate on the specific performance, variation of temperature and pressure drop are investigated. The results indicate that a three segments of segmented micro-channel, fin width-1 mm, fin length-2 mm, fin transverse distance-5 mm and channel width-1 mm have successfully enhance the heat transfer performance with minimum pressure drop. It is also found that the optimized micro-channel heat sink is able to cool the chip with heat flux of 800 W to 56.6 °C and pumping power of 0.13 W using 15 gs^{-1} of water.

1. Introduction

Rapid development of the IT industry has caused tremendous increment in the heat generation of the IC chips while air cooling technology has reached its limit. The most challenging issues faced by the industry in designing an electronic devices is to overcome the heat dissipation issue caused by scaling down the size of the device while increasing the power handling capability as well as the chip density [1]. The statistics from the International Technology Roadmap for Semiconductor (ITRS) indicate that, the power density generated by an electronic device could reach 100 Wcm^{-2} by 2020 [2]. On the other hand, the heat load could even reach 1000 Wcm^{-2} using intensive heat generation devices such as laser weapon and radar. Therefore, thermal management technology using micro-channel heat sinks has gained a great extent of popularity due to its superior heat removal capabilities through small-scale surface area in comparison to the conventional heat sink [3]. In view of this, the use of micro-channel heat sink can be found in a wide range of applications, such as military and defence, bio-

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Nomenclature

A_c	free flow area, m^2
A_f	total convective heat transfer area in contact with the fluid, m^2
A_s	total heat transfer area, m^2
C_p	specific heat capacity, J·kg^{-1}·K^{-1}
D_h	hydraulic diameter, m
f	friction factor
G	mass flux of water based on minimum flow area, $(\frac{\dot{m}}{A_c})$ kg·m^{-2} s^{-1}
$\bar{h}$	convection heat transfer coefficient, W·m^{-2}·K^{-1}
L	length of the heat sink
k	thermal conductivity, W·m^{-1}·K^{-1}
$\dot{m}$	mass flow rate of water, kg·s^{-1}
$\max x_0^i(k)$	maximum value of $x_i^0(k)$ for the k^{th} response
$\min x_0^i(k)$	minimum value of $x_i^0(k)$ for the k^{th} response
n	number of simulation run
Nu	Nusselt number
p	pressure, Pa
PD	pressure drop
$\dot{Q}$	amount of heat generated, W
$\dot{Q}_{conv}$	amount of heat dissipated through convection, W
$\dot{Q}_{rad}$	amount of heat dissipated through radiation, W
$\dot{Q}_{loss}$	amount of heat loss due to poor insulation, W
Re	Reynolds number
r_h	hydraulic radius, m
SP	specific performance
$\bar{T}_s$	average surface temperature, K
T	temperature, K
TV	temperature variation
u	velocity, m/s
U_∞	inlet velocity of water, m·s^{-1}
V	volume of the heat sink, m^3
$\dot{V}$	volumetric flow rate, m^3 s^{-1}
V_f	total fluid volume inside the heat sink, m^3
w_k	normalized weight value of k^{th} performance characteristic
W_{pp}	pumping power, W
$x_i^0(k)$	normalized value of the k^{th} element in the i^{th} sequence
$x_i(k)$	value after the grey relational generation
$x_0^*(k)$	referential sequence
$x_i^*(k)$	comparative sequence
Y_i	performance value of the simulation ith
Δ_{min}	smallest value of Δ_{0i}, 0
Δ_{max}	largest value of Δ_{0i}, 1
Δp	pressure drop through heat sink, Pa
$\Delta\theta$	change of temperature, K
Δ_{0i}	deviation sequence between reference sequence and the comparable sequence with $x_0^*(k) = 1$

Greek symbol

η	signal to noise ratio
ρ	density, kg·m^{-3}
μ	dynamic viscosity, kg·m^{-1}·s^{-1}
γ_i	overall grey relational grade for i^{th} experiment
ψ	distinguishing or identification coefficient

Subscripts

in	inlet
max	maximum
out	outlet

engineering, medical, nuclear industry, solar cell, fuel cell and electronic devices [4].

Micro-channel heat sink was initially introduced by Tuckerman and Pease to improve the heat transfer performance of a conventional macro-channel heat sink [5,6]. It was found that the thermal resistance of the cooling target is reduced by increasing the aspect ratio of the channel to surface area and it is able to dissipate a maximum heat load of 790 Wcm^{-2}. Additionally, the heat transfer performance is improved with the use of micro-channel as a result of the increased surface area to volume ratio. As a consequence, it can support greater packaging density in the future without worrying the heat generation issue [1,6]. Furthermore, Balasubramanian et al. have conducted an experimental study on a straight and expanding micro-channel heat sink with similar dimensions and operating conditions [7]. The micro-channel is made from a copper block with dimensions of 25 mm (length) × 25 mm (width) and channel width is about 300 µm. From the experiment, it is observed that the expanding micro-channel heat sink is able to provide better stabilizing effect as compared to the straight-channel heat sink. The pressure drop across the expanding micro-channel is 30% less than the straight-channel with lower pumping power to dissipate the same amount of heat flux. Although the expanding micro-channel heat sink has a lower convective heat transfer area, the thermal performance is relatively higher than that of the straight-channel heat sink. On the hand, a wavy micro-channel has been introduced by Lin et al. to further improve the heat dissipation performance of the heat sink by varying the wavelength and the amplitude of the wavy micro-channel [8]. As the wavelength or amplitude increases, the thermal resistance and variation of temperature of the cooling target is reduced. On top of that, flow disruption in a wavy channel promotes vortex creation which aids in coolant mixing and subsequently enhances the micro-channel heat sink performance. Besides, Chai et al. have conducted a series of numerical analysis to investigate the flow and heat transfer characteristics of an interrupted micro-channel heat sink by installing different configurations of ribs in the transverse micro-chambers [9]. Based on the simulation results obtained, it is demonstrated that the heat transfer performance of an interrupted micro-channel heat sink is comparatively greater than that of a straight- channel heat sink owing to the enhanced heat transfer coefficient through fluid mixing and re-initialization of the thermal boundary layer in the micro-channel heat sink. Besides, Pan et al. have investigated methanol stream reforming in the micro-channel reactors [10]. There are two different types of micro-channel cross section, namely rectangular and tooth micro-channel, and four kinds of micro-channel distributions used in the study. The experimental results show that micro-channel distribution is the major dominant on the reaction performance of methanol steam reforming. Law et al. to analyze the heat transfer performance of the straight-channel and oblique-finned micro-channel heat sinks [11]. A 25 mm × 25 mm copper block is used to fabricate parallel micro-channels and oblique cuts of angle 27° was introduced by half of the parallel channel width. The application of oblique-finned micro-channel has successfully improved the heat transfer performance of the heat sink by 6.2 times as compared to the straight-channel. This can be attributed to the higher amount of bubbles generated in the nucleate boiling regime as well as the development of thin liquid-film in the convective boiling regime. In addition, oblique-finned micro-channel also offers more stable flow boiling process as compared to the straight-channel.

On the other hand, it is noted that one of the major drawbacks of straight-channel design in micro-channel heat sink is the decreased cooling efficiency along channel flow path, which subsequently leads to large temperature difference between upstream and downstream of the heated surface. To counter this problem, secondary flow can be