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A numerical and experimental investigation of heat transfer and fluid flow characteristics of a cross-connected alternating converging–diverging channel heat sink

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ABSTRACT

In this study, the conjugate heat transfer performance of an enhanced planar heat sink design, comprising cross-connected alternating converging–diverging channels, was analyzed for forced air convection conditions. Numerical simulations were performed in ANSYS Fluent 15.0 using the RNG k–ε turbulence model accompanied by the enhanced wall treatment option to resolve the air flow and evaluate the heat transfer. Numerical results, which were validated experimentally, were utilized to investigate the flow and the temperature fields. The converging–diverging channel sections induced secondary flows through the cross connections, repeatedly disturbing the thermal and hydraulic boundary layers over the leading edges of the fin sections. The performance of the proposed heat sink design was benchmarked against the conventional straight channel heat sink of equivalent dimensions. Significant heat transfer enhancement was observed. However, the vortices, generated as a result of the separation of the secondary flows, were observed to prevent the heat transfer performance from being further improved and cause an excessive increase in the pressure drop penalty.

1. Introduction

The ever increasing heat dissipation of electronic devices requires proper thermal management. Being safe in an electrical environment, adequate in performance and readily available in the atmosphere, air has been in use as the conventional cooling medium since the invention of electronics. However, recent advances to improve the device performances resulted in an increase in their power dissipation, making it quite challenging to design air-based heat dissipation mechanisms that are capable of keeping device operation temperatures at reasonable levels. For proper functioning and satisfactory equipment life span, the device temperatures should be kept homogeneous and the maximum device temperature, determined by the manufacturer, should not be exceeded [1]. The insufficient cooling performance of air, due to its low density and specific heat, led to the development of single and two phase liquid cooling systems, which are not as easy to implement, safe to use and cost effective as air cooling [2]. Although it may be feasible to use such liquid cooling systems in high power, stationary computing facilities or data centers, their usage may not be suitable for standard user oriented and/or mobile equipment such as tablets, notebook and desktop computers, avionics or defense systems electronics etc., which have stricter size and weight limitations, and safety and reliability issues. For these reasons, air-cooling will always continue to be preferred in future electronic devices and it requires better heat sinks that are capable of maintaining lower junction temperatures while operating at reasonable fan power.

Rodgers et al. [3] stated that enhancing the air cooling performance requires an optimization of the entire heat transfer chain beginning from the heat dissipating component to the external environment to which the heat is sunk. The air flow is a vital part of this chain and a careful tailoring of the air flow could help to increase the cooling performance. There have been many attempts to improve the heat transfer performance of heat sinks with fin design modulations. Various flow phenomena observed in such designs were investigated numerically and/or experimentally. Thermal boundary layer disruption, advection heat transfer enhancement and flow attract the attention of the researchers. Since the attempts to improve the heat transfer performance of heat sinks have shifted from air cooling to single and two phase liquid cooling, the presented literature review was not kept limited to air cooling studies.

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Nomenclature

a	amplitude of the Sinusoidal channels
A	area
c_p	specific heat
CCACDC HS	cross-connected alternating converging–diverging channel heat sink
D	diameter
exp	experimental
E	enhancement/penalty factor
f	friction factor
h	convection coefficient
H	height
I	current
k	thermal conductivity
L	length
$\dot{m}$	mass flow rate
Nu	Nusselt number
num	numerical
p_{fan}	fan power
P	pressure
Pr	Prandtl number
$\dot{Q}$	heating power
R	thermal resistance
SC HS	straight channel heat sink
T	temperature
V	voltage
u	velocity
w	width

Greek symbols

α	thermal diffusivity
δ	uncertainty of a parameter
Δ	gradient (difference)
λ	wavelength of the Sinusoidal functions
μ	dynamic viscosity
ν	kinematic viscosity
ρ	density

Subscripts

avg	average
ch	channel
cond	conduction
conv	convection
cr sec	cross section
HS	heat sink
in	inlet
hyd	hydraulic
min	minimum
max	maximum
out	outlet

Saini and Webb [4] experimentally investigated the heat transfer performances of three different types of heat sinks: plain fin (straight channel), offset strip fin and circular pin fin heat sink. The heat sink dimensions were taken the same for a fair comparison and kept limited to represent real case scenarios. The fan power was the limiting parameter. The plain fin heat sink yielded a lower thermal resistance (0.221 K/W) in impinging flow configuration than the duct flow configuration (0.305 K/W). On the other hand, the offset strip fin in duct flow and the pin fin heat sink in impinging flow yielded convective resistances of 0.313 K/W and 0.385 K/W, respectively at the fan balance points. Therefore, the conventional plain fin heat sink design outperformed the enhanced designs due to the pressure loses. The study was not supported with flow visualization experiments.

Kishimoto and Sasaki [5] performed a very successful experimental study to enhance the liquid cooled straight microchannel heat sinks. The diamond-shaped micro pin fins were arranged in a staggered configuration so that the thermal boundary layers from the up and downstream did not affect each other. Thanks to the successful thinning of the thermal boundary layer, the junction temperature was decreased by 30 °C at the heat sink outlet compared to the straight microchannel heat sink. Since the leading and the trailing edges of the fins resembled the streamlines of the flow, no significant increase in the pressure drop was observed.

Ibrahim and Gomaa [6] numerically and experimentally investigated the performances of elliptic and circular tube bundles, assembled in staggered configuration, under crossflow. The flow field investigation of the successfully validated numerical results supported the experimental findings of [4] and [5]. The flow recirculation observed at the downstream of the circular tubes incurred a significant pressure drop penalty and hindered the heat transfer; while the elliptic tubes reduced the pressure drop penalty by delaying or preventing the fluid separation, and increased the heat transfer performance by successful disturbance of the boundary layers.

Another popular method to improve the air-cooled heat sink performance is to increase the turbulence intensity of the flow to reduce the boundary layer thicknesses, or to induce vortices to enhance the advection heat transfer and the flow mixing. Peng et al. [7] investigated the thermal and hydraulic performances of a wavy finned tube heat sink geometry. It was shown that the vortices, generated in the vicinity of the corrugation regions, increased the velocity gradient at the wall and decreased the thermal boundary layer thickness. However, as the air flow rate was increased, recirculation regions were observed to form within the wavy wall sections at high wave angles, reducing the heat transfer performance by hindering advection heat transfer.

Ghaedamini et al. [8] studied the flow structures in converging–diverging walled microchannels numerically. An increase in the heat transfer performance was observed at low channel waviness levels and it was attributed to the increase in the effective heat transfer area. At medium waviness levels, counter rotating vortices were found to form in the narrowest region of the channels. These vortices reduced the effective heat transfer area, therefore caused a decrease in the heat transfer performance. However, as the waviness of the channels was further increased, the vortices gained a chaotic nature, inducing a significant fluid mixing by chaotic advection and boosting the heat transfer performance significantly. The flow mixing induced by the wavy walled microchannels was demonstrated by the use of Poincarè maps.

DeJong and Jacobi [9] performed an experimental study on louvered fin arrays that could enhance air side heat transfer by boundary layer disruption. An experimental flow visualization study was also performed with a dye injection method and vortices generated between the adjacent louvers were visualized. It was found that the vortices were encompassed within the region between the louvers at low Reynolds numbers, whereas they started to be discharged to the main stream of the flow as the air mass flow rate was increased. Vortex shedding was observed to improve the mass transfer of air, therefore the heat transfer performance.

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