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Pushing the limits of vertical naturally-cooled heatsinks; Calculations and design methodology

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ABSTRACT

Heatsinks are essential parts of any thermal management system. High performance heatsinks are required for the cooling systems to be able to manage the ever-increasing power density in electronics and power electronics. The focus of this paper is on the design of high performance naturally-cooled heatsinks with vertical rectangular interrupted fins. A systematic analytical approach is taken, to solve the governing equations of the air flow and heat transfer. Closed-form correlations are presented for temperature and velocity distribution, and an easy-to-use method is introduced to design such heatsinks. Numerical simulations are used to provide better understanding of the physics of flow and heat transfer mechanism. An extensive experimental study is also conducted to verify the results from analytical solution and numerical simulation. Results show that the new-designed heatsinks are capable of dissipating heat up to 5 times more than currently available naturally-cooled heatsinks, with up to 30% less weight. The new heatsinks can increase the capacity of passive thermal management systems significantly.

1. Introduction

Thermal management of electronics/power electronics has wide applications in different industries such as; telecommunication (datacenters and outdoor enclosures), automotive (conventional, hybrid, electric, and fuel cell vehicles), renewable energy systems (solar panels and wind turbine), etc. About 55% of failures in electronics during operation has thermal root [1]. The rate of failure due to overheating, nearly doubles with every 10 °C increase above the operating temperature [2]. Considering the ever-increasing desire to miniaturization in the industry, which leads to higher power densities, thermal management has become the limiting factor in the development of such devices, and reliable low-cost methods of cooling are more and more required. The importance of efficient thermal management systems is also reflected in the market. Thermal management technology market was valued at $10.1 billion in 2013 and reached $10.6 billion in 2014. Total market value is expected to reach $14.7 billion by 2019 [3]. Thermal management hardware, e.g. fans and heatsinks, accounts for about 84% of the total market. Other cooling product segments, e.g. software, thermal interface materials (TIM), and substrates, each account for 4–6% of the market [3].

Passive cooling is a widely preferred cooling method for electronic and power electronic devices. High reliability, no noise and no parasitic power make natural convection and other passive cooling methods attractive for sustainable and "green" systems. As an example, in telecom industry, integrating passive cooling techniques with conventional cooling strategies can reduce the energy required for thermal management from 28% of total energy consumption [4], to 15% in general [5] and 0% in some cases [6].

Considering an available temperature difference between the heat source and cooling medium, this thermal budget is always spent in the thermal resistances along the heat path. These thermal resistances, in most cases include: (i) thermal contact resistance at the solid–solid interface, (ii) spreading resistance, due to changes in geometry, (iii) bulk resistance, due to the materials' thermophysical properties, and (iv) film resistance existing at the solid–fluid interface due to thermal boundary layer. Except for the film resistance, the rest of above-mentioned thermal resistances are acting similarly between active and passive cooling systems. The effect of film resistance appears in the heatsink, and consequently design of high performance naturally-cooled heatsinks becomes very important in a fully passive thermal management system.

This paper provides an easy-to-use design method for a specific type of naturally-cooled heatsinks, namely interrupted fins. Naturally-cooled heatsinks with interrupted fins are shown to have very high performance compared to continuous fins, staggered

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Nomenclature

General symbols

A	surface area, m^2
c_p	specific heat, J/kg K
g	gravitational acceleration, m/s^2
G	gap length, m
Gr	Grashof number, $g\beta\Delta Ts^3/\nu^2$
h	heat transfer coefficient, W/m^2 K
H	fin height, m
k	thermal conductivity, W/m K
l	fin length, m
L	baseplate length, m
m	number of fin rows
n	number of fin columns
Nu	Nusselt number, hs/k
P	heater power, W
Pr	Prandtl number, ν/α
$\dot{q}$	heat flux, W/m^2
$\dot{Q}$	total heat transfer, W
Ra	Rayleigh number, $g\beta\Delta Ts^3/\nu\alpha$
s	fin spacing, m
t	thickness, m
T	temperature, K
u	velocity in x-direction, m/s
v	velocity in y-direction, m/s
W	baseplate width, m
x	direction parallel to fins, m
y	direction normal to fins, m
z	direction normal to x and y in Cartesian coordinate

Greek symbols

α	thermal diffusivity, m^2/s
β	coefficient of volume expansion, K^{-1}
Δ	difference
ε	channel slenderness, l/s
ϕ	coefficient appears in gap velocity
φ	coefficient appears in gap velocity
ι	coefficient appears in gap temperature
μ	dynamic viscosity, kg/m s
ν	kinematic viscosity, m^2/s
ϑ	constant appears in gap temperature
ρ	density, kg/m^3
σ	parameter appears in gap temperature, 1/m
ς	parameter appears in gap velocity, 1/m
ω_R	uncertainty
ξ	gap width, m

Subscripts

∞	ambient properties
C	channel
$C.V.$	control volume
G	gap
in	inlet of channel/gap
$N.C.$	natural convection
out	outlet of channel/gap
$Rad.$	radiation
$total$	total heat transfer
w	wall properties

interrupted fins, and even pin fins [7], and they currently exist in the market (Fig. 1a), mostly used for military applications that require high reliability, and high mechanical strength. Interruptions are discontinuities added fins to postpone the thermal boundary layer emergence in the channel flow between two adjacent walls (Fig. 1b); thus increase the total heat transfer rate [8]. Additionally, interruptions lead to considerable weight reduction, which in turn, can lower the manufacturing and material costs. It should be noted that interrupted fin arrangement is a more general form of geometry and includes both continuous and pin fins at the limit. Where the interruption length approaches zero or the fin length approached to the values close to fin thickness, continuous fin and pin fin geometries are respectively. In other words, continuous and pin fins are two extreme cases of the targeted interrupted fins. Fin interruption is common in industry and have been extensively studied for internal natural convection [9,10] and forced convection [11]. However, to the authors' best knowledge no comprehensive study is available for natural convection from interrupted fins. The present study aims to address this shortcoming.

1.1. Literature review

A general overview on pertinent literature in the area of natural convection heat transfer from fins is provided in this section. The focus of this study is on natural convection heat transfer from vertical rectangular interrupted fins.

1.1.1. Single wall

A variety of theoretical expressions, graphical correlations and empirical equations have been developed to calculate the coefficient of natural convection heat transfer from vertical plates. Ostrach [12] made an important contribution on analyzing the natural convection heat transfer from a vertical wall. He analytically solved laminar boundary layer equations using similarity methods for uniform fin temperature condition and developed a relationship for the Nusselt number for different values of Prandtl number. As well, Sparrow and Gregg [13] used similarity solutions for boundary layer equations for the cases of uniform surface heat flux. Merkin [14], also used similarity solution to solve natural convection heat transfer from a vertical plate with non-uniform wall temperature and wall heat flux. Churchill and Chu [15] developed an expression for Nusselt number for all ranges of the Rayleigh, and Pr numbers. Yovanovich and Jafarpur [16] studied the effect of orientation on natural convection heat transfer from finite plates. Cai and Zhang [17] found an explicit analytical solution for laminar natural convection in both heating and cooling boundary conditions.

1.1.2. Parallel plates

Finned surfaces are widely used for enhancement of heat transfer [18,19]. Natural convection heat transfer from vertical rectangular fins is a well-established subject in the literature. Pioneering analytical work in this area was carried out by Elenbaas [20]. He investigated isothermal finned heatsink semi-analytically and experimentally. His study resulted in general relation for average Nusselt number for vertical rectangular fins; which was not accurate for small values of fin spacing. Churchill [21] and Churchill and Chu [15] developed a general correlation for the average Nusselt number for vertical channels using the theoretical and experimental results reported by a number of