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Full Length Article

Improved thermal management of computer microprocessors using cylindrical-coordinate micro-fin heat sink with artificial surface roughness

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ABSTRACT

In this work, numerical study on the thermal behaviour and subsequent heat transfer enhancement of cylindrical micro-fin heat sink with artificial surface roughness is analyzed using Chebychev spectral collocation method. The developed thermal models consider variable thermal properties in accordance with linear, exponential and power laws. The numerical solutions are used to carry out parametric studies and to establish the thermal performance enhancement of the rough fins over the existing smooth fins. Following the results obtained from simulations, it is established that the thermal efficiency of the micro-fin is significantly affected by the geometric ratio, nonlinear thermal conductivity parameter, thermo-geometric parameter and the surface roughness of the micro-fin. In addition, the results show that geometric ratio and the surface roughness of the fin enhance its thermal performance. The fin efficiency ratio which is the ratio of the efficiency of the rough fin to the efficiency of the smooth fin is found to be greater than unity when the rough and the smooth fins are subjected to the same operations with the same geometrical, physical, thermal and material properties. From the investigation, it is established that improved thermal management of electronic and thermal systems can be achieved through the use of artificial rough surface fins or heat sink.

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1. Introduction

The proliferation in demand for high-performance electronic systems often comes with inherent thermal challenges. With the thermal challenges for the present and next-generation electronics systems [1], the need to combate excess heat generation has been on the increase. Effective cooling technology or thermal management of microprocessors in most electronic devices including notebook and computers has been one of the key goals in modern-day advanced electronic design. To achieve this goal, active and passive modes of cooling technologies have been deployed. However, the active modes of heat transfer enhancement or augmentation such as fans, blowers, fluid vibration, surface vibration, suction and jet impingement and electrostatic fields have proved economically inviable due to their operating costs. An alternative means of thermal cooling is the applications of passive methods such as extended surfaces and treated surfaces, which have shown to be effective thermal management technology [2]. As one of the passive modes of thermal cooling technology, fin or extended surface are used to enhance the rate of heat transfer from thermal and electronic systems. Although there is a high record of thermal performance of extended surfaces in both electronic and thermal systems [3–16], the quest for more highly efficient, miniaturized, lightweight heat sink or fin with reduced thermal resistance continues. In search of such high-performance fin heat sink in their investigations, Zhou et al. [17] and Ventola et al. [2] advocated for the use of artificial surface roughness for transfer enhancement through extended surfaces. Consequently, different methods have proposed the application of artificial surface roughness in heat transfer surfaces [18–22]. However, experimental and theoretical investigations on thermal analysis of artificial rough surface micro-fins with application to microprocessors are limited. Nonetheless, Bahrami [23] presented a study on the effects of random rough surface on thermal performance of micro-fin. Diez et al. [24] applied the power series to analyze the thermal performance of rough micro-fins of three different profiles, namely, hyperbolic, trapezoidal and concave. Recently, several other authors carried out different numerical studies on the enhanced thermal

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Nomenclature

A_b	Cross-sectional area at the fin base, m^2
A_c	Cross-sectional area of the fin, m^2
$\overline{A}_c$	Average cross-sectional area of the rough fin, m^2
A_s	Surface area of the fin exposed to convection, m^2
$\overline{A}_s$	Average surface area of the rough fin exposed to convection, m^2
B_i	Biot number, given by $2r_bh/k$
k	Fin thermal conductivity, $Wm^{-1}K^{-1}$
L	Fin length, m^2
m	Thermo-geometric parameter, m^{-1}
m_σ	Mean absolute surface slope
M^2	Extended Biot number,
n	Heat transfer coefficient constant
P	Fin perimeter, m
q	Heat transfer rate,W
r	Fin radius, m
$\overline{r}$	Average radius of a rough fin, m
r_δ	Random variation of the fin radius in the angular direction, m
r_b	Radius at the fin base, m
r_L	Random variation of the fin radius in the longitudinal direction, m
r_t	Radius at the fin tip, m
T	Temperature, K
T_b	Base temperature, K
T_∞	Fluid temperature, K
M_c	Thermo-geometric ratio
x	Longitudinal coordinate, m
x_b	Position of base for the hyperbolic fin, m
x_t	Position of tip for the hyperbolic fin, m
z	Longitudinal coordinate, m

Greek symbols

$\mathscr{E}$	Relative roughness
φ	Dimensionless coordinate
η	Fin efficiency ratio
λ	Length of the arc of the fin profile, m
θ	Dimensionless temperature
σ	Isotropic surface roughness, m
σ_δ	Fin surface roughness in the angular direction, m
σ_L	Fin surface roughness in the longitudinal direction, m
ξ	Geometric ratio
ψ	Dimensionless coordinate

management of microprocessors heat sink using micro-fins with artificial surface roughness and variable thermal properties [24–29]. In most of these works, consideration is placed on the thermal performance in conductive-convective fins, with assumed constant thermal properties. However, such assumption becomes inaccurate with large temperature difference existing between the fin base and its tip. Therefore, this paper presents a numerical study on the thermal analysis and management of microprocessors using cylindrical rough pin micro-fin with variable thermal properties in a convective-radiative environment. The study is carried out to establish the influence of roughness, variable thermal performance, convective, radiative heat transfer on the thermal performance of the micro-fin. In addition, the developed thermal models are solved numerically using Chebychev spectral collocation method (CSCM) and simulated using ode45 in MATLAB.CSCM is an effective numerical approach that solves nonlinear integral and differential equations without linearization, discretization, closure, restrictive assumptions, perturbation, approximations, round-off error and discretization which often results in massive numerical computations. CSCM reduces the complexity of expansion of derivatives and the computational difficulties of the other traditional approximation analytical or perturbation methods. In addition, CSCM provides excellent approximations to the solution of non-linear equations with high accuracy, minimal calculation, and avoidance of physically unrealistic assumptions. It is not affected by computation round-off errors, whilst there is non-requisite for large computer memory and time. CSCM offers fast rate of convergence with a very large converging speed when compared with other numerical methods. The converging speed of the approximated numerical solution to the primitive problem is faster than one expressed by any power-index of *N-1*. The main advantage of CSCM lies in their accuracy for a given number of unknowns. For smooth problems in simple geometries, they offer exponential rates of convergence/spectral accuracy [30,31]. Thus CSCM is suitable for the present study for improved thermal management. Furthermore, this study is timely since most electronic/computer devices require efficient, miniaturized cooling system. A key advantage of miniaturized heat sink with fan size is the reduction on the airflow rate and control of acoustic level, which results in lower distortion, an increases the lifespan on the electronic or computer component.The paper is organized as follows: In Section 2 we formulate the problem using cylindrical micro-fin with a rough surface. Section 3 presents the mathematical modeling of the rough surface, whilst in Section 4 we apply the CSCM to solve the developed thermal models in Section 3. Section 5 presents the fin efficiency. The results generated using MATLAB is presented and discussed in detailed in Section 6, whilst the paper concludes in Section 7.

2. Problem formulation

Consider a heat sink of a microprocessor is made up of rough cylindrical micro-fin shown in Fig. 1. Assume the fin is of dimension length L and thickness t, and exposed on both faces and subjected to a convective-radiative environment with temperature T_a, whilst no thermal contact resistance exists at the fin base. In addition, the micro-fin surface roughness is random and obeys a Gaussian probability distribution in the angular and longitudinal direction.For one-dimensional heat flow and following the assumptions stated above, the governing equations for the heat transfer in the fin can be summed as [32]:

$$\frac{d}{dx}\left(-k(T)A_c\frac{dT}{dx}\right)+h(T)P(T-T_\infty)=0 \tag{1}$$

The boundary conditions are given as:

$$x=0,\quad T=T_bx=L,\quad \frac{dT}{dx}=0 \tag{2}$$

The thermal conductivity of the micro-pin–fin can vary linearly as

$$k(T)=k_a(1+\lambda(T-T_\infty)) \tag{3a}$$

or exponentially as

$$k(T)=k_ae^{\lambda(T-T_\infty)}. \tag{3b}$$

The convective heat transfer coefficient will vary as

$$h(T)=h_b\left(\frac{T-T_\infty}{T_b-T_\infty}\right)^n. \tag{3c}$$

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