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Effect of fin shape on the thermal performance of nanofluid-cooled micro pin-fin heat sinks

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ABSTRACT

The study presents the combined effects of using nanofluid and varying fin cross-sectional shape on the heat transfer characteristics of a micro pin-fin heat sink by employing discrete phase model (DPM). Three fins configurations of the square, circular and hexagon cross-section with constant fin diameter and height have been analyzed for the inline arrangement of 17×34 fins. Aqueous nanofluid containing spherical shaped particle dispersions of TiO_2 has been simulated for the particle concentration and size of 4.31 vol% and 30 nm respectively. Constant heat flux (192 W) boundary condition at the base of heat sink has been considered for the range of Reynolds number $250 \leq Re \leq 550$. The influence of fin shape on the thermal efficiency of the heat sink has been analyzed by evaluating heat sink base temperature, Nusselt number, convective heat transfer coefficient distribution and temperature contours along the surface of the heat sink. Additionally the velocity streamlines and contours have also displayed to elaborate the fluid flow attributes. Results demonstrate that under identical flow conditions, the nanofluid cooled circular fins displayed most efficient thermal performance followed by the hexagon and square fins. While the water cooled square fins depicted lowest heat transfers characteristics. The best thermal performance of the circular fins is the response of the delayed flow separation along the smooth surface of fins and the subsequent uniform flow distribution along the whole sink. For all the cases, upstream fin rows played a primary contribution in flow distribution and hence thermal characteristics of the heat sink.

1. Introduction

Thermal management is one of the prime technical challenges encountered by modern electronics. The paradigm shift in mechanical designs to satisfy the appetite of power, speed and miniaturization requires innovative cooling techniques. In this pursuit, among other passive techniques such as engineered surface texturing, microchannels and fins [1–6], the adoption of novel coolants with improved thermo-physical properties has attracted great attention over the years. Early scientists tried to suspend micrometer-sized particles with high thermal conductivity in traditional coolants to improve their thermal properties. However undesirable features prompted by micron-sized metallic particles i.e. rapid sedimentation, clogging, erosion and immense pressure drop renounced the practicality of technology until advancements in colloid and interface science allowed its revision with nanoparticles.

Nanofluids, the conventional thermo-fluids (e.g. water, oil, ethylene glycol) comprises nano-sized metallic or nonmetallic suspended particles with anomalously optimized thermal conductivity. Additionally, nanofluids exhibit high stability, minimum particle agglomeration, flexible properties and enlarged particle effective surface for optimum inter-phase heat exchange. Moreover, slight pressure drop and mechanical deterioration makes nanofluids extremely feasible for new generation compact heat exchangers. Since past two decades, multiple experimental and numerical studies have been carried out in order to explore hydrothermal characteristics of various types of nanofluids. The multiple theories postulated so far, described thermal activity augmentation of the nanofluids as a consequence of various micro-scale complicated mechanisms including particle rotation, clustering, fluid layers encapsulating the particles, Brownian motion associated with micro-convection, particle migrations and corresponding non-uniform property profiles as well as disruption of the boundary layer [7–17]. The recent biographical reviews summarizing the progress in exploring the thermal characteristics of the nanofluids with various formulations are available in Refs. [18–21].

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Nomenclature

A	area (m^2)
C_p	specific heat (J/kg K)
C_c	Cunningham correlation (–)
d_{fin}	fin hydraulic diameter (m)
d_h	hydraulic diameter of heat sink (m)
d_{ij}	deformation tensor (–)
DPM	discrete phase model (–)
F	force ($N/kg\ m^3$)
f	Darcy friction factor (–)
F_{drag}	drag force ($N/kg\ m^3$)
$F_{gravity}$	gravity force ($N/kg\ m^3$)
F_{lift}	Saffman Lift ($N/kg\ m^3$)
$F_{pressure}$	pressure gradient force ($N/kg\ m^3$)
$F_{thermophoresis}$	thermophoresis force ($N/kg\ m^3$)
$F_{virtual}$	force due to virtual mass($N/kg\ m^3$)
g	gravitation acceleration (m/s^2)
$GNPs$	graphene Nano-platelets
h	convective heat transfer coefficient ($W/m^2\ K$)
h_b	thickness of the heat sink base (m)
h_{fin}	fin height (m)
h_s	channel height (m)
m	mass (kg)
k	thermal conductivity (W/mk)
L_1	total length of the heat sink (m)
L_2	total length of the active area (m)
K_B	Boltzmann constant ($m^2\ kg/s\ K$)
K_n	Knudson number (–)
Pr	Prandtl number (–)
Re	Reynolds number (–)
S_u	source term (energy equation)
S_E	source term (momentum equation)
T	temperature (K)
t	time (s)
t_F	total No. of fins
TiO_2	titanium dioxide (–)
V	fluid total velocity (m/s)
W_1	Total width of the heat sink (m)
W_2	total width of the active area (m)
w_c	channel width (m)
w_{fin}	fin width (m)
$Y+$	dimensionless wall distance of first node (–)

Greek Symbols

λ	molecular mean free path (m)
μ	viscosity (-)
ρ	density of fluid [$kg\ m^{-3}$]
φ	particle weight concentration (–)
∇T	temperature change of the continuous phase

Subscripts

avg	average
b	base
c	channel
eff	effective

Greek Symbols

fin	fin
f	fluid
h	hydraulic
nf	nanofluid
p	particle
s	surface
T	reference temperature

Another popular thermal enhancement technique is optimization of heat sink geometry with the aim of improving fluid-structure interactions. Consequently, mini-channels and eventually micro pin-fin heat sinks (hydraulic diameter 10–1000 μm) were introduced in recent years [22–26]. Characterized by low thermal resistance and uniform temperature distribution, micro pin-fin heat sinks offer a compact solution for thermal management of electronic devices. The high thermal efficiency of these heat-sinks is not merely because of the larger effective surface area but also the disruption of the hydrothermal boundary layer and augmented fluid mixing plays a significant role [27–30]. In addition to size, material and arrangement of fins, the shape of fins strongly influences the viscous-thermal boundary layers and wake behind fins [29,31–37]. Ricci and Montelpare [33] experimentally investigated the influence of fin cross-sectional shape on the thermal performance of water-cooled pin-fin heat sink by considering an inline arrangement of three fins. Their results showed a stronger dependence of Nusselt number on fin shape and position. Of all the tested fins shapes (circular, square, triangular and rhomboidal), the triangular and rhomboidal fins exhibited superior heat transfer attributes. Kosar and Peles [34] considered staggered circular, rectangular, hydrofoil and cone-shaped fins for their experimental analysis and concluded that at a moderate flow rate and pressure drop, the utilization of streamlined fins is favorable for water-cooled pin-fin heat sink. However, when pressure drop and flow rate are either low or high, fin shapes stimulating flow separation are desirable. John et al. [35] carried out a parametric study on micro pin-fin heat sinks with inline fin arrangement cooled by water. Their computed results showed that at low Reynolds number ($Re\ \langle 3\ 0\ 0$) the circular fins displayed better hydrothermal performance (based on their figure of merit FOM) as compared to the heat sink with square fins but at higher Reynolds number ($Re >$ 300) opposite trend was observed. In a similar numerical analysis, Tullius et al. [29] studied staggered assembly of square, circular, triangular, ellipse, diamond and hexagon shaped fins aligned in a microchannel. The triangular and hexagon fins showed highest Nusselt number and pressure drop respectively. The circular and ellipse showed lowest pressure drop and Nusselt number. Their results also revealed little sensitivity of heat sink performance towards fin material in comparison to fin shape, width, height and spacing. Later on, Abdoli et al. [36] analyzed circular, hydrofoil, modified hydrofoil and convex lens fin configurations (staggered pattern) and observed that the convex and hydrofoil shaped micro pin-fin heat sink revealed lowest pressure drop. Recently Yang et al. [37] studied rhombus, hydrofoil and sine shaped micro pin-fin heat sinks by numerical and experimental means. Their results displayed that sine shaped micro pin-fin heat sink exhibit most promising heat transfer as well as pressure drop characteristics. In contrast to conventional fluids, a limited number of studies evaluated the performance of pin-fin heat sink by using nanofluids as coolant. Duangthongsuk and Wongwises [38] carried out an experimental investigation on the pin-fin heat sink (inline array of circular fins) by utilizing ZnO/water and SiO_2/water nanofluids and concluded that addition of nanoparticles in the water optimizes the heat transfer rate with a little expense of pressure drop. Later on Ali and Arshad [39,40] experimentally analyzed the thermal