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Technical Note

Optimization of a staggered pin-fin for a radial heat sink under free convection

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ABSTRACT

The design of a staggered pin-fin radial heat sink was optimized for light-emitting diode (LED) device cooling. A numerical model for various pin-fin array heat sinks was developed and verified experimentally. The design variables were determined from sensitivity analysis. Multidisciplinary optimization was conducted based on the heat sink thermal resistance and mass, using an evolutionary algorithm. From the analysis results, the staggered pin-fin radial heat sink was identified as the optimal configuration, demonstrating improved thermal performance by up to 10% while maintaining the same mass or reducing the mass by up to 12% for a given thermal resistance.

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1. Introduction

Light-emitting diodes (LEDs) are an eco-friendly item, offering a long lifetime and high energy conversion efficiency. Thus, much existing lighting has been replaced by LED devices. An abrupt increase in the temperature of the LED chip results in a sharply reduced lifetime and considerably lower light emission efficiency. Studies have shown that 60% of the input power to the LED is converted into thermal energy, as evidenced by the high heat flux [1]. Therefore, it is necessary to cool the LED system sufficiently for stable light emission. The most common passive cooling device for the electrics is a heat sink. Heat sinks are becoming increasingly larger and heavier to accommodate the increasing thermal performance demands of LED devices, at the expense of the lighting device's safety and manufacturing cost. Thus, technology is needed to improve the performance of the heat sink while reducing its mass.

Recently, numerous studies have investigated the cooling effects of radial heat sinks applied to LED down light and high bay devices [2–4]. Yu et al. [2,3] analyzed the thermal performance of various plate-fin radial heat sinks using a numerical method with natural convection considerations; the long fin and middle fin type heat sink was identified as the heat sink with the best thermal performance. Jang et al. [4] applied multidisciplinary design optimization to a pin-fin radial heat sink with thermal resistance and mass as the key factors; however, their study targeted radial heat sinks having only an in-line array. Deshmukh et al. [5] and Bahadur et al. [6] examined in-line and staggered pin-fin arrays in a square heat sink set on a vertical wall. Chen et al. [7] and Yuan et al. [8] studied the thermal performance of staggered array heat sinks by forced convection. However, this study focusses on the thermal performance of the heat sink by natural convection.

In the present study, a staggered pin-fin radial heat sink mounted on a horizontal wall was considered for LED device cooling. Sensitivity analysis was used to identify the geometric factors that had a significant influence on the heat sink mass and its thermal performance. The heat sink design was further modified via multidisciplinary design optimization.

2. Mathematical modeling

2.1. Numerical model

Fig. 1(a) shows the staggered pin-fin radial heat sink, the focus of this study. The heat sink consisted of a circular base with pin-fin arrays positioned periodically along the perimeter of the circular base. Fig. 1(b) and (c) show the computational analysis domain, including the heat sink and surrounding air. To minimize the computing time, only one period domain was analyzed with periodic conditions [9–11]. The following assumptions were adopted to simulate natural convection and radiation heat transfer.

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Nomenclature

A	surface area
g	gravity
H	height [mm]
h	heat transfer coefficient [W/m^2 °C]
k	thermal conductivity [W/m °C]
L	length [mm]
M	mass of heat sink [kg]
N	number of fin array
$\dot{q}$	heat flux [W/m^2]
R_{TH}	thermal resistance [°C/W]
r	radius [mm]
T	temperature [°C]
t	thickness of fin [mm]
w	weight factor
y	height from base [mm]

Greek symbols

ε	emissivity

Subscripts

acr	acrylic
ave	average
c	characteristic
facet	facet of cell
F	fin
i	inner
L	long fin
M	middle fin
o	outer
ref	reference
S	space between fins
∞	ambient

(1) The flow is laminar, steady, and three dimensional.
(2) The air properties are constant, with the exception of the density.
(3) Air is an ideal gas.
(4) The surfaces of the heat sink are gray and diffuse.

Radiation heat transfer was calculated using the discrete transfer radiation model (DTRM) [12], given periodic conditions.

2.2. Numerical method

The radius and height of the analysis domain ranged from $1.2r_o$ to $1.8r_o$ and $2H$ to $8H$, respectively. Values of $1.5r_o$ and $5H$ were selected as the domain size in which the average temperature variation of the heat sink was small (1%). A quadrilateral mesh was used; the mesh distance became narrower close to the heat sink surfaces, in the proximity of the predicted existence of the boundary layer. The parameters of the reference heat sink were $N = 20$, $L_L = 40$ mm, $L_M = 20$ mm, $L_F = 4$ mm, $L_S = 5$ mm, $r_o = 90$ mm, $r_i = 5$ mm, $H = 40$ mm, $t = 3$ mm. The grid dependence was considered by changing the number of grids from 104,946 to 881,725 in the reference model. Grid points totaling 518,312 were set as the reference, given that the average temperature variation of the heat sink was <1%. Numerical analysis was performed using ANSYS FLUENT *release 14.5*, a commercial computational fluid dynamics (CFD) code based on the finite volume method; the mesh was generated using the ANSYS ICEM *release 14.5*. The semi-implicit method for pressure linked equations (SIMPLE) algorithm was used to calculate the flow field based on the pressure and velocity. The convective term and energy equation were discretized with the second-order upwind scheme. The convergence criteria for the dependent variables was set to 10^{-5}.

3. Experiment and validation

The heat sink was made from aluminum alloy 6061 ($k = 171$ W/m °C) with a black anodizing surface treatment ($\varepsilon = 0.9$) for the validation procedure. The parameters of the heat sink were $N = 24$,

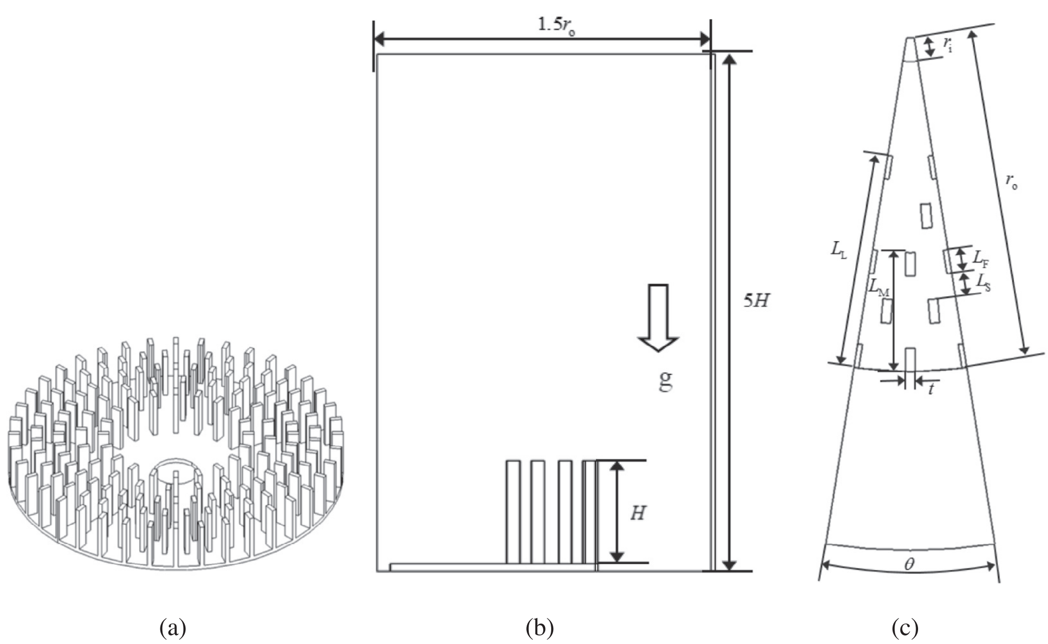

Fig. 1. Schematic diagram of a heat sink and computational analysis domain: (a) isometric view (b) top view (c) side view.

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