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Research Paper

Numerical analysis of the effect of a central cylindrical opening on the heat transfer of radial heat sinks for different orientations

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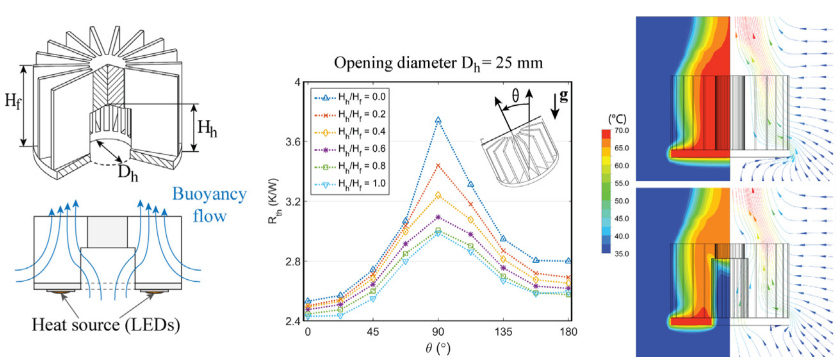
HIGHLIGHTS

- Natural convective cooling of radial heat sinks with central opening is analyzed.
- The new design effectively reduces orientation sensitivity of radial heat sinks.
- Thermal resistance is reduced by up to 30.5% for same heat sink base area.
- Nusselt number correlation are proposed for three different orientations.
- The findings of the study are valuable for high-power LED lighting applications.

GRAPHICAL ABSTRACT



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ABSTRACT

This paper presents a numerical study aimed to improve the natural convective cooling design of radial heat sinks used for light emitting diode (LED) bulbs. The improved design utilizes a central opening on the bottom that allows an additional natural cooling flow through the center of the fin array. First, the optimum fin spacing of a standard radial heat sink was determined and used as a reference geometry to compare the degree of improvement. By comparing different heat sink orientations, it was found that the opening can improve the orientation sensitivity by reducing the maximum difference in thermal resistance from 47.1% to 22.4%. At the orientations with $\theta = 0°$, 90°, and 180°, the thermal resistance of the radial heat sink was reduced by up to 4.3, 30.5, and 14.3 K/W, respectively. The effect of geometric parameters was investigated revealing that a larger opening diameter and height lead to a lower thermal resistance. The numerical model was further used to visualize the natural convective cooling flow through the fin array. For the acquired data set practical *Nu*-correlations including dimensionless parameters accounting for the height and diameter of the opening are proposed.

1. Introduction

Light-emitting diodes (LEDs) are semiconductor light sources, which outperform most other illumination technologies in terms of efficiency, durability, versatility and cost-effectiveness. The worldwide annual energy consumption for lighting is estimated to be around 19% of the total global electricity production, which illustrates the high potential of LED lights [1]. However, one of the main challenges when designing LED applications is reliable and adequate thermal management. LEDs only convert about 20–30% of the energy to light, while the rest is released as heat.

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Nomenclature

A	surface area of the heat sink, m^2
b	thickness of heat sink base, mm
D	diameter, mm
El	Elenbaas number
g	gravitational acceleration, m/s^2
h	heat transfer coefficient, W/m^2 K
H	height, mm
k	conductivity, W/m K
N	number of fins
Nu	Nusselt number
P	pressure, Pa
Pr	Prandtl number
Q	heat source power, W
R_{th}	thermal resistance, K/W
S	source term of energy equation
s	fin spacing, mm
T	temperature, °C
t	fin thickness, mm
u, v, w	velocity components in x, y, z directions

Subscripts

a	ambient
avg	average
b	base
i	inner
h	opening
o	outer
f	fin
s	surface

Greek symbols

α	thermal diffusivity, m^2/s
β	volumetric thermal expansion coefficient, 1/K
ε	emissivity
ν	kinematic viscosity, m^2/s
ρ	density, kg/m^3
θ	orientation angle

Abbreviations

CFD	computational fluid dynamics
LED	light emitting diode
RMSE	root mean square error

A 10–15 °C increase in the LED junction temperature can reduce its lifetime by up to 50%, and at higher temperatures the chip runs less efficient and emits less light [2]. Thus, optimizing the thermal management leads to better light quality, longer lifetime and, as a result, a more reliable lighting product.

Cooling of LEDs can be either active or passive via natural convection. While the feasibility of active cooling systems has been demonstrated in numerous studies [3–6], they all include moving parts, which result in higher manufacturing costs, increased complexity, additional energy consumption, regular maintenance, and the addition of new potential failure mechanisms [7]. Therefore, active cooling is more appropriate for special lighting applications with very high power inputs than for the cooling of consumer products, such as LED light bulbs. Passive cooling, or natural convective cooling, is driven by buoyancy forces due to density differences. The key component of most passive cooled LEDs is a heat sink. The challenge is to design a low cost, lightweight heat sink with a large surface area that also complies with the shape and size restrictions of standard lighting products. The advantages of natural convection heat sinks are a long lifespan, zero power consumption, low to zero maintenance, and no noise [2]. Major drawbacks of passive cooling are a lower thermal performance, dependency of orientation [8], and high influence of surrounding obstacles such as lamp shades or ceilings.

Consequently, many recent studies have focused on the analysis and improvement of heat sinks for LED applications. These studies can be roughly divided into rectangular [8–10] or radial [11–24], according to the outer shape of the heat sinks. Rectangular heat sinks are mainly used for LED applications with power inputs of over 30 W, such as large flood and outdoor lights. Smaller LED applications, such as spot lights and light bulbs, commonly use radial heat sinks with straight fins, which are also the focus of the present study. Costa and Lopez [13] presented an improvement strategy to obtain the ideal radial heat sink, by considering the number of fins, fin height, fin length, and fin thickness. Multiple studies, which compared the orientation dependency of radial heat sinks [14–16], concluded that when the center axis is oriented vertically (θ = 0° or 180°), the thermal performance is clearly better than when oriented horizontally (θ = 90°). Li and Byon [15] found that radial heat sinks at an orientation of 90° have an approximately 20.4% and 12.5% higher thermal resistance than heat sinks oriented at 0° and 180°, respectively. This orientation dependency can be significantly reduced by replacing the straight fins with pin or cross-cut fins [16]. Park et al. [22] analyzed and optimized a chimney design for radial heat sinks, which enhanced the thermal efficiency by moving the cooling air flow closer to the center of the fin array. Another chimney design, where the sides of the fins are partially covered, was proposed and studied by Li et al. [23]. The authors found that the chimney-based heat sink enhanced the thermal performance by up to 20% compared with a standard radial heat sink.

Although many studies focus on optimizing radial heat sinks, they all essentially assume that either the central core or the base of the heat sink is closed, which limits the convective cooling flow to the outside. Many LED lamps utilize an array of individual LED chips, instead of a single chip. These individual LED chips are often arranged in a single or double symmetrical circular array [12,20], which allows a central opening in the middle of the individual chips. This way, a convective cooling flow through the center of the heat sink, where the heat axis is located, can be realized. Two previous studies designed and analyzed LED light bulbs with this type of central opening [25,26]. First, Petroski [25] presented and analyzed three different LED bulb prototypes with chimney type light guides and the equivalent dimensions of a standard A19 bulb. At an input power of 12 W, Petroski's optimized design reduced the thermal resistance to 3.1 K/W and 3.83 K/W for the vertical and horizontal orientation. Second, Jang et al. [26] investigated a novel light bulb, where the printed circuit boards form a channel and act as cooling fins. The authors concluded that their design could considerably reduce the orientation sensitivity and expand the life span of the LED bulb by 40% compared to traditional geometries.

Similar to the two abovementioned studies, the present study focuses on an LED bulb design with a cooling flow through the center; however, instead of developing a special design, this study modifies a standard radial heat sink. The main aim is to design and analyze the thermal performance of a radial heat sink with a