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Optimization of a chimney design for cooling efficiency of a radial heat sink in a LED downlight

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ABSTRACT

A cooling system, consisting of a chimney and a radial heat sink, was developed for a light-emitting diode (LED) downlight to replace a conventional light for saving energy. Natural convection was simulated with a numerical model that was verified experimentally. When the chimney was installed around the radial heat sink, the cooling efficiency of the heat sink was improved because the cooling air was able to move to the center of the heat sink. Furthermore, the mass of the surrounding structure could be reduced due to the superior geometric characteristics of the chimney versus a hollow cylinder. The effects of the fin-type of the radial heat sink and the thermal conductivity of the chimney were analyzed. A parametric study of the geometric factors of the chimney was conducted and a multidisciplinary design optimization, which considered the chimney mass and cooling efficiency of the heat sink, was carried out. Consequently, installing the chimney can improve the heat sink's cooling efficiency by up to 20% (while maintaining the mass of the surrounding structure) or reduce the mass of the surrounding structure by up to 60% (for a given cooling efficiency), as compared to the installation of the hollow cylinder.

1. Introduction

The demand for the development of high-efficiency electric has been increased in an attempt to reduce the emission of greenhouse gases [1]. Lighting accounts for about 20% of the world's electric energy consumption; therefore, high-efficiency lights are needed to replace conventional lights [2–4]. Accordingly, the lighting industry has been replacing conventional lights with light-emitting diode (LED) lights, which offer higher energy conversion efficiencies and longer life times [5]. However, the high temperature of an LED chip causes a reduced life time and degeneration of the light emission stability [6,7]. A heat sink is a general cooling system that is used for electrical items like LED lights. For example, the LED downlight in Fig. 1 manages the LED chip temperature with a radial heat sink, which has a circular base surface [8]. Recently, the heat release rate from LED chips has been increased due to the increased power that is needed for brighter lights. Thus, research on fin geometry optimization has been conducted to increase the thermal performance of heat sinks [9–11]. However, complex fin geometries raise mass production costs. Thus, it is important to develop a cooling system that can improve the cooling efficiency of the heat sink without changing the fin geometry.

Many studies have investigated methods to enhance natural convection by controlling the flow paths. Mey et al. [12] installed a cylindrical-surrounding structure around vertical fins and found the optimal set-up height of the structure. da Silva and Gosselin [13] increased the heat transfer rate of a vertical heated surface by modifying the inlet and outlet geometry of the channel. However, the radial heat sink in this study has a horizontal heated surface, so the results of these studies are not applicable. Shimoyama et al. [14] enhanced the natural convection at a horizontal heated surface by installing a heated cylindrical-surrounding structure. Park et al. [15] investigated the improvement of the cooling efficiency of a radial heat sink with a hollow cylinder. However, the installation of surrounding structures increases the mass of the cooling system. Increasing in the mass of the lighting system will raise the mass production costs and weaken the market competitive power. Thus, the design optimization research to decrease the mass of the surrounding structure and improve the cooling efficiency of the radial heat sink is needed. Li et al. [16] suggested a chimney-based radial heat sink that added a structure on the outside of the radial heat sink. However, the chimney-based radial heat sink is difficult to mass-produce with extrusion and die casting processes. Also, the improvement in the cooling efficiency was less than the improvement obtained by installing the hollow cylinder [15].

In this study, a chimney-surrounding structure that improves the cooling efficiency of the radial heat sink and decreases the

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Nomenclature

A	surface area of heat sink base (m^2)
C_μ, $C_{1\varepsilon,2\varepsilon}$	turbulent constant
G_k	generation of turbulent kinetic energy
g	gravity acceleration (m/s^2)
H	height (mm)
h	heat transfer coefficient (W/m^2 °C)
k	kinetic energy of turbulence (m^2/s^2)/thermal conductivity (W/m °C)
L	length (mm)
N	number of fin arrays
M	mass of surrounding structure (g)
$\dot{m}$	mass flow rate (g/s)
p	pressure (Pa)
$\dot{Q}$	heat transfer rate (W)
$\dot{q}$	heat flux (W/m^2)
R_{th}	thermal resistance (°C/W)
r	radius (mm)
T	temperature (°C)
t	thickness (m/s)
u	velocity component (m/s)
x	distance (mm)
Y	non-dimensional geometric parameter
y	geometric parameter (mm)

Greek symbols

α	effective inverse Prandtl number
ε	dissipation rate of turbulent kinetic energy (m^2/s^3)
μ	dynamic viscosity (m^2/s)
ρ	density (kg/m^3)
τ	shear stress (Pa)
ω	weighting factor

Subscripts

a	air
ave	average
b	base
c	chimney
eff	effective
f	fin
g	thermal resistant glass
h	heat sink
i	inner
in	input
l	long fin
m	middle fin
o	outer
op	operating
ref	reference
s	surrounding air

mass of the surrounding structure was developed. The chimney design was also optimized. A numerical model, validated by experiments, was used for simulating the thermal flow around the radial heat sink and chimney. The applicability of various fin-type radial heat sinks and the effects of different chimney materials were analyzed. A parametric study of various chimney geometric factors was conducted and a multidisciplinary design optimization, considering the mass and the cooling efficiency of the radial heat sink, was carried out.

2. Mathematical modeling

2.1. Numerical model

Fig. 2 shows a chimney-surrounding structure and a radial heat sink, which are the objects of this study. The radial heat sink is a long fin and middle fin (LM) type, as suggested by Yu et al. [17]. LMs are positioned periodically on the base surface. The chimney consists of a ring-shaped horizontal plate portion and a cylindrical pipe portion. Fig. 3 shows the computational domain that contains the radial heat sink, chimney and surrounding air. To minimize the computational effort, only one period domain was calculated by applying periodic conditions at periodic interfaces of the fluid and solid domains [18]. Pressure inlet/outlet conditions were applied to outer surfaces of the fluid domain. On the base surface of the heat sink, the constant heat flux condition was used. The following assumptions were used to simulate the thermal flow:

(1) The flow is steady.
(2) The properties of the air and solids are independent of the temperature except for air density.

Fig. 1. LED downlight with a radial heat sink.

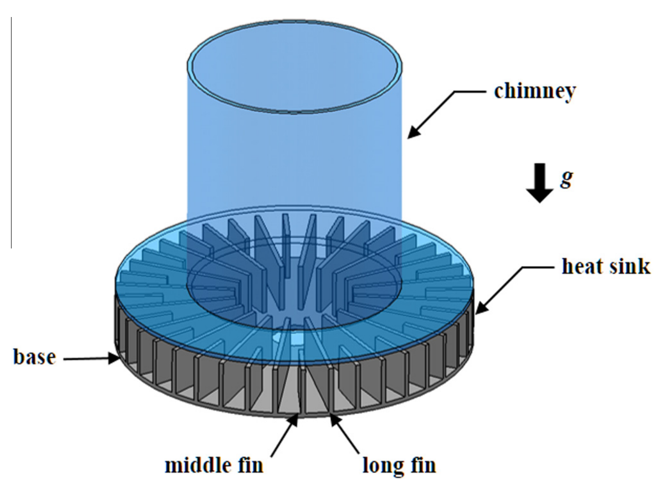

Fig. 2. Schematic diagram of the chimney and LM-type radial heat sink.