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The orientation effect for cylindrical heat sinks with application to LED light bulbs

Daeseok Jang, Seung-Jae Park, Se-Jin Yook, Kwan-Soo Lee *

School of Mechanical Engineering, Hanyang University, 222 Wangsimni-ro, Seongdong-gu, Seoul 133-791, Republic of Korea

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ABSTRACT

This research examined the orientation effect for a cylindrical heat sink used to cool an LED light bulb. Natural convection and radiation were taken into account in the simulation, and the numerical model was validated experimentally. Changes in the cooling performance of a cylindrical heat sink with increasing angle of inclination were examined. The orientation effect was analyzed by considering the flow characteristics and drag coefficient, and the influence of geometric parameters on the cooling performance of a cylindrical heat sink was evaluated. The orientation effect was intensified when the number of fins and the fin length increased, whereas the influence of fin height on the orientation effect was relatively insignificant. Finally, a correlation was proposed to predict the Nusselt number around an inclined cylindrical heat sink.

1. Introduction

LED lighting offers a longer life span and higher energy efficiency than conventional lighting. Because of these advantages, LED lighting is rapidly replacing conventional lighting in the lighting market. LED light bulbs are used in various situations, and the angle of inclination of these light bulbs varies according to the application. This angle can significantly affect the cooling performance of the heat sinks used in conjunction with LED lighting. If an LED light bulb is operated under low cooling performance, the luminant efficiency of the LED chip decreases. LED light bulbs are typically cooled with cylindrical heat sinks, as shown in Fig. 1. Therefore, it is necessary to study the effect of the angle of inclination on the cooling performance of cylindrical heat sinks.

Radial heat sinks for cooling LED lights have recently been investigated due to the rapid development of the LED lighting market. Yu et al. [2–4] and Jang et al. [5] studied natural convection heat sinks with vertical fins attached to a horizontal circular base. They analyzed the thermo-flow characteristics around these radial heat sinks, and optimized their cooling performance and mass. However, these studies were concerned only with heat sinks for down lights, which are horizontally attached to the ceiling. Therefore, the results are inapplicable to cylindrical heat sinks used for other types of LEDs, such as the light bulb considered in the present study. An et al. [6] studied natural convection around cylindrical heat sinks for a light bulb. A Nusselt number correlation for various heat-sink geometries was obtained experimentally, and an optimum number of fins was proposed. However, that study considered only the horizontal orientation, and did not investigate the changes in cooling performance with respect to various product-use environments. If the angle of inclination changes, the effects of design parameters on the cooling performance of the heat sink also changes. In this case, the optimum design of the heat sink is different from the optimum design of An et al. [6]. Elenbaas [7] conducted pioneering research on the orientation effect (i.e., changes in natural convection cooling performance according to the angle of inclination). He experimentally analyzed the orientation effect for parallel plates. Starner and McManus [8] carried out experiments to measure the heat-transfer coefficient in four cases of rectangular heat-sink geometry and three cases of heat-sink orientation. Sparrow and Vemuri [9] conducted an experimental study of the orientation effect for rectangular pin–fin heat sinks. They found that the cooling performance was outstanding with a vertical upward-facing orientation, and determined the optimum fin population. Ledezma and Bejan [10] numerically and experimentally investigated the orientation effect for inclined plate–fin heat sinks under natural convection and radiation heat transfer. Huang et al. [11] carried out an experimental study of the orientation effect for square pin–fin heat sinks, and proposed an optimum porosity and finning factor according to orientation considering the fin height. Sertkaya et al. [12] experimentally investigated the orientation effect for pin–fin heat sinks, and found that the cooling performance was outstanding with an upward-facing orientation. Do et al. [13] studied the natural convection heat transfer of inclined rectangular plate–fin heat sinks for concentrating

* Corresponding author. Tel.: +82 2 2220 0426; fax: +82 2 2295 9021.
E-mail address: ksleehy@hanyang.ac.kr (K.-S. Lee).

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Nomenclature

C	specific heat [J/(kg K)]
C_D	total drag coefficient
C_{DF}	friction drag coefficient
C_{DP}	pressure drag coefficient
C_p	pressure coefficient
D	diameter of heat sink [mm]
F_{DF}	friction drag force [N]
F_{DP}	pressure drag force [N]
Gr	Grashof number
g	gravitational acceleration [m/s^2]
H	fin height [mm]
h	heat-transfer coefficient [W/(m^2 K)]
k	thermal conductivity [W/(m K)]
L	length [mm]
N	number of fins
Nu	Nusselt number
n	normal direction vector
P	pressure [Pa]
$\dot{Q}$	heat-transfer rate [W]
$\dot{q}$	heat flux [W/m^2]
R_{TH}	thermal resistance [°C/W]
s	surface
t	fin thickness [mm]
V	velocity [m/s]
w_c	fin-to-fin spacing

Greek symbols

β	coefficient of volume expansion [K^{-1}]
δ	thermal boundary layer thickness
σ	Stefan–Boltzmann constant [W/m^2·K^4]
ρ	density [kg/m^3]
ε	emissivity
θ	angle of inclination [°]
τ	shear stress [Pa]

Subscripts

avg	average
c	characteristic
f	film temperature
L	average over the heat-sink length
i	inner
o	outer
p	projected in flow direction
rad	radiation
∞	ambient

photovoltaic (CPV) modules. They showed that the error in the correlation by Bar–Cohen et al. [14] became larger with increasing angle of inclination, and they then proposed an improved correlation that closely matched experimental data over a wide range of angles of inclination. Tari and Mehrtash [15] numerically analyzed the flow characteristics around inclined rectangular heat sinks, and obtained a correlation covering a wide range of angles of inclination. In the case of a rectangular heat sink, the orientation effects on plate fins are identical because the fins are parallel to each other. However, the fins of a cylindrical heat sink are circularly arrayed; if a cylindrical heat sink is inclined, the flow pattern around the fins varies according to the fin position. Thus, the results of previous studies regarding the effect of orientation on rectangular heat sinks are inapplicable to cylindrical heat sinks. Although a considerable amount of research has been conducted on the orientation effect, the influence of geometric parameters on the orientation effect has not been investigated to the best of our knowledge. Additionally, most of the previous studies analyzed the orientation effect in terms of the cooling performance estimated from measured heat-sink temperatures. Although these studies explained the results of the orientation effect, their quantitative analyses of its causes were insufficient.

A number of researchers have investigated changes in cooling performance by analyzing the flow characteristics and drag coefficient. Jia and Gogos [16] conducted a numerical study of natural convection around a sphere, and obtained the heat-transfer coefficient and drag coefficient. They concluded that the drag coefficient decreased and the ratio of the pressure drag coefficient to total drag coefficient increased with increasing Grashof number. Mittelman et al. [17] examined the flow characteristics of downward-facing fin arrays via experimental, numerical, and analytical techniques. They found that a downward-facing fin array interrupted the plume flow generated by buoyant forces, resulting in a stagnation point that degraded cooling performance. Samsal and Chhabra [18] studied the effect of aspect ratio on natural convection in power-law liquids surrounding a horizontal elliptic cylinder. They found that the drag force of a bluff body shape with a high aspect ratio was greater than that of a slender body shape with a low aspect ratio, and that pressure drag was the dominant component of the total drag force, resulting in a decreased Nusselt number. However, these studies are inapplicable to the cooling of LED light bulbs. Furthermore, the orientation effect on heat sinks has not been analyzed in terms of the drag coefficient. Therefore, it is necessary to investigate the orientation effect on a cylindrical heat sink.

Fig. 1. Cylindrical heat sink for an LED light bulb [1].

The present study investigates the orientation effect for cylindrical heat sinks used to cool an LED light bulb. The numerical model, which considers both natural convection and radiation heat transfer, is validated experimentally. The orientation effect for cylindrical heat sinks is examined by analyzing the flow characteristics and drag coefficient. Additionally, the influence of geometric variables (i.e., the number of fins (N), fin length (L), and fin height (H)) on the orientation effect is studied. Finally, a correlation is proposed to predict the Nusselt number around a cylindrical heat sink with respect to the geometric parameters, angle of inclination, and heat flux.

2. Mathematical modeling

2.1. Numerical model

Fig. 2 shows the type of heat sink investigated in the present study. The heat sink consists of a cylindrical base and vertical plate fins. The fins are circularly arrayed at regular angular intervals.