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# Thermal performance of a PCB channel heat sink for LED light bulbs

Daeseok Jang, Seung-Jae Park, 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

In this study, the thermal performance of the printed circuit board (PCB) as a heat sink for the light-emitting diode (LED) bulb is analyzed. Cooling air is drawn through the bottom inlet of a case and exchanges heat from a vertically aligned PCB acting as a heat sink fin. The air then exits through a top outlet. Cooling performance is improved by arranging parallel PCBs to form a channel. Heat transfer is optimized by balancing cooling airflow rates on external and internal PCB surfaces, thereby reducing thermal resistance by 30% compared to previous designs. Cooling performance according to installation angle is investigated. The orientation effect on this channel design is determined to be 10% less than that of the reference design. Finally, the effect of PCB channel cooling performance on the LED bulb's life span is analyzed and shown to be 40% longer than that of the existing geometry.

## 1. Introduction

Recent trends in light-emitting diode (LED) lighting focus on high energy efficiency and low environmental impact. Owing to the low efficiency of existing incandescent light bulbs, their production and importation are prohibited in China and will be fully banned in 2016. Alternatives to the incandescent bulb are compact fluorescent lamps (CFLs) and halogen lamps. CFLs contain harmful substances, such as mercury; therefore, their demand has decreased. Halogen lamps (25 lm/W) provide greater energy efficiency than incandescent bulbs (15 lm/W); however, they are less efficient than LEDs (75 lm/W). On account of planned EU committee energy efficiency regulations, halogen lamps will also be prohibited in 2016. Environmentally friendly, energy-efficient LED bulbs are encroaching on the existing light bulb market; nevertheless, insufficient heat dissipation in LEDs reduces light emission efficiency and shortens the expected life span. Therefore, research is needed on the cooling performance of LEDs.

Several recent studies have investigated radial heat sinks for LED lights. Yu et al. [1,2] and Jang et al. [3,4] surveyed natural convection heat sinks with vertical fins on a horizontal circular plate. However, these studies were limited to heat sinks for ceiling-mounted downlights. Kulha et al. [5] analyzed the thermal performance of LEDs by conducting finite element method (FEM)-based thermal simulations. The results were in good agreement with experimental results collected using a thermal infrared camera and contact temperature measurements. Jiří et al. [6] investigated thermal modeling and characterization of LEDs and showed that high-temperature solder joints are vulnerable to thermal stress. They stated that the reliability of the bulb would be improved by reinforcing those parts of the design. Petroski [7] examined a wide range of heat sinks, such as annular chimneys, Y-chambers, and inner-fin heat sinks for heat dissipation in LED bulbs with powers equivalent to 60 W or more. Jeng et al. [8] studied LED cooling systems using forced convection. In these studies, the A19 design or bulb shape constraints restrict the design of heat sinks or forced convection cooling systems. Because conventional incandescent A19 bulbs emit omnidirectional light, heat sinks and forced convection structures attached to LEDs impose limitations on the emission patterns, resulting in directional light. An ideal solution cools LEDs by natural convection and matches the A19 form, which is the ANSI standard [9]. Recently, LED bulbs [10] without external aluminum heat sinks were developed using the printed circuit board (PCB) as a heat sink. These bulbs have almost the same appearance as conventional incandescent bulbs, but they are lighter and have attracted attention as a new type of LED light bulb.

The thermal performance of LED light bulbs using PCBs as heat sinks is herein analyzed. The flow characteristics and thermal performance of the cooling apparatus (perforated vents on the bulb case and PCB heat sink) are investigated. Furthermore, the effect of the PCB installation angle on thermal performance is examined. Finally, the effect of cooling performance on the LED life span is studied.

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* 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

| | |
|---|---|
| $A$ | heat transfer area [m$^2$] |
| $B$ | projected initial constant derived by the least-squares curve fit |
| $C$ | specific heat [J/(kg K)] |
| $E_a$ | activation energy [eV] |
| $\mathbf{F}$ | body force vector per unit volume |
| $g$ | gravity acceleration [m/s$^2$] |
| $h$ | height [mm] |
| $k$ | thermal conductivity [W/(m K)] |
| $k_B$ | Boltzmann's constant [eV/K] |
| $L$ | lumen maintenance life [hours] |
| $l$ | length [mm] |
| $\dot{m}$ | mass flow rate [kg/s] |
| $n$ | normal direction vector |
| $n_r$ | refractive index |
| $P$ | electric power [W] |
| $\dot{Q}$ | heat transfer rate [W] |
| $R_{TH}$ | thermal resistance [°C/W] |
| $S$ | source term [W/m$^3$] |
| $s$ | surface |
| $T$ | temperature [K] |
| $t$ | time [s] |
| $u$ | velocity [m/s] |
| $\mathbf{v}$ | velocity vector [m/s] |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | decay rate constant |
| $\beta$ | coefficient of volume expansion [K$^{-1}$] |
| $\gamma$ | thermal loss ratio, $\frac{\dot{Q}_{net}}{P_{convert,\ DC}}$ |
| $\eta$ | power factor, $\frac{P_{convert,\ DC}}{P_{supply,\ AC}}$ |
| $\rho$ | density [kg/m$^3$] |
| $\Phi$ | averaged normalized luminous flux output |
| $\varepsilon$ | emissivity |
| $\theta$ | angle of inclination [°] |

*Subscripts*

| | |
|---|---|
| offset | offset between PCB channels |
| h | heat |
| i | in situ |
| p | maintained lumen output percentage |
| s | soldering (case) |
| w | wall |
| $\infty$ | ambient |

## 2. Mathematical modeling

### 2.1. Numerical model

Fig. 1 shows a typical LED bulb, which is the focus of this study. The bulb and screw base were respectively designed to ANSI standards A19 and E26. Vents were patterned in the top and bottom of the bulb to enable the flow of cooling air. The PCB consisted of four intersecting planes that were perpendicularly aligned. By placing an LED chip on each side of the PCB, the bulb emitted omnidirectional light, much like the filament of an incandescent bulb. To make the analysis domain independent of the installation angle, a sphere whose center was the center of the bulb was set as a control volume (see Fig. 2). The following assumptions were applied for numerical analysis.

(1) Flow is three-dimensional and laminar.
(2) Air density is calculated by the ideal gas law [11].
(3) PCB surfaces are gray and diffuse [10].

The following governing equations were applied for numerical analysis.

*Fluid region*

Continuity equation:

$$\nabla \cdot (\rho \mathbf{v}) = 0. \tag{1}$$

Momentum equation:

$$\rho \frac{D\mathbf{v}}{Dt} = -\nabla P + \mu \nabla^2 \mathbf{v} + \mathbf{F} \ (\text{for z-direction } \mathbf{F} = -\rho g). \tag{2}$$

Energy equation:

$$\rho C \frac{DT}{Dt} = \nabla \cdot (k \nabla T) + \frac{DP}{Dt}. \tag{3}$$

*Solid region*

$$\rho C \frac{DT}{Dt} = \nabla \cdot (k \nabla T) + S_h. \tag{4}$$

The LED chip was treated as a volumetric heat source; its heat generation was applied as a term ($S_h$) in the energy equations. The boundary conditions are indicated in Table 1. The radiative heat transfer model was calculated using a discrete ordinates model [11].

### 2.2. Numerical methods

To couple the pressure and velocity in numerical analysis, the SIMPLE algorithm was applied. Using a second-order upwind scheme, the convection term of each governing equation and energy equation was discretized. The iterative convergence criterion was that the maximum relative error of dependent variables was less than $10^{-5}$. Considering the time taken to converge on a solution for PCB temperature, the computational domain radius was investigated from one to three times the height of the bulb. As a result, a domain 1.8 times the height of the bulb, with a temperature variation less than 0.5%, was selected. Considering the grid dependency, the number of elements was tested from 750,000 to 3,800,000. From that point, a mesh of 2,403,454 elements was selected on account of its temperature variation of less than 0.5%.

## 3. Experiment and validation

Experiments were performed to validate the numerical model using the configuration shown in Fig. 3(a). Temperatures were measured using thermocouples (Omega TT-T-36 SLE) at four PCB solder points and three ambient air points. The PCB and diffuser case emissivities were calculated for numerical analysis by indirect measurements using an infrared thermal camera. They were determined to be $\varepsilon_{PCB} = 0.84$ and $\varepsilon_{Diffuser\ case} = 0.9$, respectively. Thermal resistance was selected as a performance index for evaluating the cooling performance of the PCB. It is defined as follows:

$$R_{TH} = \frac{(T_{soldering} - T_\infty)}{\dot{Q}_{net}}, \tag{5}$$

where

$$\dot{Q}_{net} = \eta \gamma P_{supply,AC}, \quad \eta = \frac{P_{convert,DC}}{P_{supply,AC}}, \quad \gamma = \frac{\dot{Q}_{net}}{P_{convert,DC}}.$$