Thermoelectric transformation and illuminative performance analysis of a novel LED-MGVC device☆∗

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A B S T R A C T
Energy-efficient, small and lightweight high-power light-emitting diodes (Hi-LEDs) are combined with a thermogeneration module (TGM) to transform the heat power generated by the LED into electric energy in the present paper. Variation in the dielectric copper and solder layer thickness in the printed circuit board (PCB) composite was found to affect the thermal performance of the Hi-LEDs lighting system, and a vapor chamber (VC) was shown to provide excellent heat dissipation performance when used with Hi-LEDs. Therefore, VC and PCB (VCPBC) were combined for integration with the Hi-LEDs package system (micro-generator with LED vapor chamber-based plate, LED-MGVC) for performance and illumination comparison. This study analyzes the performance of a novel LED-MGVC device using experimental and illumination-analysis methods with VCTM V1.0. Results depict that the LED-MGVC system provides significant improvement for thermal performance and illumination and thermoelectric properties.

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1. Introduction

Compared with traditional incandescent lamps, high-power light-emitting diodes (Hi-LEDs) technology presents significant benefits over traditional incandescent lamps and has thus begun to be aggressively used in lighting applications including street lamps, traffic lights, automobile headlights, backlights for liquid crystal display (LCD) televisions, building lighting and indoor-lighting lamps. Although LEDs are considerably more efficient than traditional lighting (15–25% vs. 10%), Hi-LEDs still produce a signficant amount of heat flux during operation [1–3]. Thus, as high-power LED arrays are used more widely for general lighting systems, they generate a more significant amount of heat flux (above 85%). LEDs can be classified as high brightness and general brightness, with high-brightness and high-power LEDs usually producing more than 1 W of heat per die. The power package of a single LED die has a surface area of 1 mm², with a total heat power of 1 W. Thus, a single high-power LED usually has a heat flux greater than 100 W/cm². This heat flux easily results in thermal hot spots at the device junction, thus reducing the life span of high-brightness LEDs.

A vapor chamber is a two-phase heat transfer component that uniformly spreads and transfers heat flow, making it ideal for use in non-uniform heating conditions such as in Hi-LEDs. The effectiveness and improved thermal performance of vapor chambers has been confirmed in prior studies through mass application in server systems and VGA thermal modules [4–6]. Wang and Wang [7] derived a novel formula for the effective thermal conductivity of vapor chambers by use of modified dimensional analysis combined with a thermal-performance experimental method. Results show that its effective thermal conductivity increases with input power above 800 W/m°C, with a margin of error of less than ± 5 %. Wang et al. [8] reported a thermal-performance experiment using the illumination-analysis program VCTM V1.0 to discuss green illumination techniques using LEDs as a solid-state luminescence source in light lamps with the application of a vapor chamber to 30 W Hi-LEDs. Virtual Basic V6.0 was used to code the theoretical models with empirical formulae for computer-aided modeling thermal modules to develop the VCTM V1.0 program for convenient use in industrial applications. A thermoelectric generating module (TGM) is making use of the Seebeck effect to convert the heat flow into electric energy through the use of thermoelectric materials [9–18]. Francisco et al. [19] utilized thermoelectric generators (TEG) and heat pipe (HP) modules based on the Seebeck effect to transform waste heat into electric energy for low (15 kW) and a high (40 kW) operating modes. Results demonstrated the potential of this system for recovering otherwise wasted heat. Kagawa et al. [20] applied a thermoelectric generator/thermo-generator to a municipal solid waste incinerator to capture low temperature thermal energy. Nevertheless, a micro-generator with LED vapor chamber-based plate (LED-MGVC) device combining LED-VCPBC [21] with TGM is shown to reduce the LED hot-spot problem and produce high levels of lighting energy efficiency.

This article uses computer-aided modeling design tools to analyze LED-MGVC performance, as shown in Fig. 1. A TGM is put on a LED vapor chamber-based plate, and the heat generated by the LED is stored in the lithium-ion battery through the Seebeck effect. It is important to use proper CAD/CAE tools in LED-MGVC design, and appropriate thermal
The current value of the best performance of the power generation chip can be derived through the basic theory of thermoelectric physical effect and the Fourier heat transfer law, with the equivalent circuit for the power generation chip shown in Fig. 3. The voltage value $V$ is generated by the thermoelectric power generation, $R_i$ is the resistor generated by the thermoelectric material and $R_c$ is the resistor compared with the applied load. According to the Seebeck effect, the voltage generated by the power generation chip is proportional to the chip temperature difference between the hot and cold ends of the power generation chip.

The current $I$ relationship of power generation chip is shown in Eq. (7).

$$I = \frac{V}{R} = \frac{\alpha \Delta T}{R_i + R_c}$$  \hspace{1cm} (7)$$

According to the conservation of energy, the energy generated $P$ by a power generation will be its power to the load $R_i$ as shown in Eq. (8). $Q_h$ and $Q_c$ are the heat capacity of the hot and cold sides, as shown in Eqs. (9) and (10), respectively. These are divided into three parts for discussion: $\alpha TH$ is the thermoelectric effect, $\frac{\pi \Delta T}{\alpha}$ indicates the Joule heat, divided equally between the hot and cold sides, and $\phi = \frac{\pi}{\alpha}$ is the Fourier effect of the heat flow from high to low temperature. The energy generated by the power generation chip $P$ is less than the heat to the cold side is the heat supply of the hot end ($Q_h - Q_c$), which is used to generate the load $R_c$. Thus, the output energy $P$ is functional to current $I$ as shown in Eq. (11). If the output energy $P$ is differentiated by the current $I$ and is then set equal to zero, the power generation chip will produce the maximum output power $P_{\text{max}}$ as shown in Eq. (12). The ratio efficiency $\eta$ of thermoelectric power generation chip is shown in Eq. (13), and the

$$P_{\text{max}} = P_{\text{max}}$$  \hspace{1cm} (12)$$

$$\eta = \frac{P_{\text{max}}}{\Phi}$$  \hspace{1cm} (13)$$

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