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

Jung-Chang Wang *

Department of Marine Engineering, National, Taiwan Ocean University (NTOU), Keelung 20224, Taiwan, ROC

A R T I C L E I N F O

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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 thermo-generation 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 (VCPCB) 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.

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 significant amount of heat flow 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 mm^2, with a total heat power of 1 W. Thus, a single high-power LED usually has a heat flux greater than 100 W/cm^2. 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 $\pm$ 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 Seeback 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-VCPCB [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

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* Corresponding author at: No.2, Beining Rd., Keelung 20224 Taiwan, ROC.
E-mail address: jcwang@ntou.edu.tw.

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Nomenclature

A	sectional area, m^2
I	electric current, A
K	thermal conductivity, W/m °C
L	length of thermoelectric element, meter
P	output energy, W
Q	heat transfer rate, W
R	thermal (or electrical) resistance, °C/W (or Ω)
T	temperature, °C
V	potential difference, V
W	width of thermoelectric element, m

Greek letters

α	Seebeck coefficient, V/K
η	ratio efficiency
π	Peltier coefficient, V
σ	material conductivity $(\Omega \cdot m)^{-1}$
τ	Thomson coefficient, W/K

Subscripts

A	air/ambient
C	cold side
h	hot side
N	N-type thermoelectric element
P	P-type thermoelectric element
eff	effective
in	input
LED-MGVC	micro-generator with LED vapor chamber-based plate
Out	output
TGM	thermo-generation module
Vc	vapor chamber

conditions were ensured through using a composite approach to LED-MGVC computer-aided modeling design. Several theoretical models for thermal modules have been developed, using software and algorithms to predict thermal, optical and electric performances in the computer-aided modeling design system, and the relevant programs and methods for computer-aided LED-MGVC design are introduced in the present paper.

2. Methodology

1. Performance analysis

Thermoelectric physical phenomena can take the form of external energy caused by temperature differences between objects to produce the potential difference for power generation. A thermoelectric power generation system must have a cold end and a hot end, with a load circuit (R_L) as shown in Fig. 2. The system operates on the basic principle of thermoelectric physical phenomena for thermoelectric semiconductors. The present study uses power generation chip analysis to analyze the thermoelectric transformation performance of LED-MGVC. LED-MGVC thermoelectric performance can be divided into the Seebeck, Peltier and Thomson effects. Eqs. (1)–(4) reveal their relational coefficients, including α, π and τ. The Seebeck effect indicates that two different metals connected in a closed loop will generate an electromotive force when the two metal contacts produce a temperature difference. The Peltier effect affects the current in a closed loop formed by the two different metals, where the physical phenomena of heat absorption and release form at both ends of the metal contacts in proportion to the amount of input current. The electromotive force of the thermoelectric power generation system is generated by the voltage addition due to the thermoelectric element within the circuit series, while the current flows through the load circuit output. The temperature difference between the cold and hot ends is due to the low thermal conductivity of the thermoelectric elements, preventing most of the heat capacity from being transmitted by the hot end to the cold side, thus maintaining the temperature difference. The merit of ZT is the judgment of thermoelectric materials, which is calculated in Eq. (5), where σ is the material conductivity of $(\Omega \cdot m)^{-1}$ and K is the thermal conductivity of W/mK. Therefore, a higher value of ZT indicates a high Seebeck coefficient and low thermal conductivity, resulting in the increased generation of thermoelectric power.

$$\alpha = -\frac{dV}{dT} \tag{1}$$

$$\pi = \frac{\left(\frac{dQ}{dT}\right)}{I} \tag{2}$$

$$\left(\frac{\pi}{\alpha}\right) = T \tag{3}$$

$$\left(\frac{\tau}{\alpha}\right) = I \tag{4}$$

$$ZT = \frac{\alpha^2 \sigma}{K} \tag{5}$$

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_L 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 sides following Eq. (6),

$$V = \alpha\left(\overline{T}h - \overline{T}c\right) \tag{6}$$

where V is the electromotive force, α is the Seebeck coefficient of the materials, $\overline{T}h$ and $\overline{T}c$ are the respective average temperatures of the hot and cold ends of the power generation chip.

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

$$I = \frac{V}{R} = \frac{\alpha \Delta T}{R_i + R_L} \tag{7}$$

According to the conservation of energy, the energy generated P by a power generation will be its power to the load R_L 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: $\alpha I Th$ is the thermoelectric effect, I^2R indicates the Joule heat, divided equally between the hot and cold sides, and $\frac{Ak(Th-Tc)}{L}$ is the Fourier effect of the heat flow from high to low temperature. The energy generated by the power generation chip P is less the heat to the cold side is the heat supply of the hot end ($Qh - Qc$), which is used to generate the load R_L. Thus, the output energy P is functional to current I as shown in Eq. (11). If the output energy P is differenced by the current I and is then set equal to zero, the power generation chip will produce the maximum output power P_{max} as shown in Eq. (12). The ratio efficiency η of thermoelectric power generation chip is shown in Eq. (13), and the