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Thermal management of multiple LEDs for high-power lighting applications

Ju Yong Cho and Won Kweon Jang*

Department of Electrical and Electronic Engineering, Hanseo University, Seosan-31962, Chungcheongnam-do South Korea

E-mail/Orcid Id:

JYC, food0421@naver.com, https://orcid.org/0000-0002-2961-2284; *WKJ,* jwk@hanseo.ac.kr, https://orcid.org/0000-0003-1779-7987

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Abstract: Power LED lighting has suffered from substantial heat generated, leading to significant performance degradation. Consequently, achieving an optimal distribution of LEDs is essential to ensure high luminance efficiency. Implementing effective thermal treatment is important to prevent any potential degradation in the performance of the LED lighting system. Optimizing the arrangement of individual LEDs is a promising approach to mitigating heat accumulation issues. In this paper, we propose a reasonable approach to obtaining the optimal distribution of LED lighting systems under DC biasing and PWM operating conditions. The thermal analysis simulation was performed based on the theoretical assumption to evaluate the thermal distribution of a single LED. Thermal analysis was conducted on an LED lighting system with 20 LEDs, and the distance between LEDs ranged from 4 mm to 24 mm. The simulated analysis showed that the maximum temperature could be controlled from 65.1 ℃ to 58.7 ℃. We discussed the optimum arrangement of LEDs and how heat generated by an LED influences the system. In addition, the LED lighting was operated in PWM mode to mitigate the thermal issues. The relationship between luminance efficiency and operation condition is discussed. Thus, the luminance efficiency improved from 114.8 lm/W to 126.8 lm/W, and the thermal relaxation time was no longer than 0.013 s. The process of determining the optimal distance between LEDs was very effective in achieving an optimized power operating condition and LEDs distribution in the module for a compact volume and enhanced performance.

Introduction

LED lightings have been widely employed in many fields of application, such as automobiles, biology, street lighting, scientific research, and the medical industry, thanks to its high luminescence efficiency and longer lifespan compared to incandescent lighting. The demand for high-power LED lighting systems in these applications has grown significantly. While luminescence efficiency has been improved drastically, it is still insufficient to meet the requirements of high-end power LED lighting. One of the major drawbacks of the power LED lighting is related to thermal issues, resulting in its performance degradation. This is because the luminescence efficiency of power LED lighting systems strongly relies on the temperature (Ho et al., 2015).

LED array that chips are mounted on a small area could be a solution for power LED lighting (Gao et al., 2023; Lin et al., 2012; Patil et al., 2023; Yu et al., 2022). However, the LED array needs significant electrical power, resulting in performance degradation caused by heat accumulation.

A heat sink is considered one of the conventional approaches to address thermal issues in high-power LED lighting (Bobaru and Rachakonda, 2004; Bouknadel et al., 2014; Lee, 1995). For the improved thermal management, alternative methods such as jet impact cooling, phase-change cooling, and the use of nanofluids have been reported (Chen et al., 2022; Jiu et al., 2022; Lin et al., 2012; Moradikazerouni, 2022; Naphon et al., 2018; Ramos-Alvarado et al., 2013; Ramesh et al., 2022). While these methods offer enhanced the heat dissipation, they often require the use of a fan, complex and costly designs, and regular maintenance, leading to disadvantages such as extra additional energy

*Corresponding Author: jwk@hanseo.ac.kr

consumption, bulkier systems, and significant noise levels (Lai et al., 2017). Hence, the passive cooling system that incorporates a heat sink remains a preferred choice in terms of cost, weight, and reliability.

Through many studies of thermal analysis have been reported with numerical analyzing results to improve the thermal dissipation performance of passive cooling systems. These studies often focus on design parameters related to the convection coefficient, resulting in various fin-shape designs such as cylindrical fins and triangular fins (Sahel et al., 2021; Haghighi et al., 2018; Alam et al., 2020; Ekpu et al., 2022).

One of the other design parameters is related to the conduction coefficient. Thermal interface materials play a crucial role in improving thermal energy transfer from the LED module to the heat sink. Innovative thermal materials were reported and evaluated (Adhikari et al., 2020; Lin et al., 2022; Liu et al., 2023; Tang et al., 2016; Mishra et al., 2019).

High-power LED lighting consists of LED arrays that are mounted on a printed circuit board (PCB). The arrangement of these LEDs significantly influences the performance of the lighting system. Therefore, optimizing the arrangement of LEDs becomes imperative in mitigating issues associated with heat accumulation. This optimization procedure involves an assessment of thermal characteristics, including thermal resistance and junction temperature, as outlined in previous works (Lai et al., 2017; Hwang et al., 2004; Zhang et al., 2022). Consequently, various configurations for arranging LEDs have been proposed as optimal designs (Abdelmlek et al., 2021; Lai et al., 2017; Rózowicz et al., 2022; Sümer et al., 2021). It is noteworthy, however, that a significant proportion of studies focusing on optimizing LED arrangements have primarily ascertained that LED temperature decreases as the distance between LEDs increases. Nevertheless, these studies often neglect the consideration of the volume of the LED array, leading to some ambiguity in determining the effectively optimal design. However, determining an optimum distance between LEDs and arranging them accordingly may allow for a reduction in the system's volume while maintaining its optical performance.

In this paper, we preliminarily conducted two-step analysis. The first step is a thermal analysis of a single LED to determine its thermal characteristics. Heat generated by individual LEDs can interfere with each other, leading to suboptimal heat transfer between the LED module and the heat sink. In order to mitigate this issue, increasing the distance between LEDs is a simple approach. However, the temperature does not decrease linearly as the distance between LEDs increases. This led us to the significant conclusion that establishing a standard distance between LEDs is a noteworthy consideration. Thermal analysis of an LED was performed to investigate thermal distribution generated by an LED. Consequently, a point at which heat interference between LEDs could be negligible was discussed. Based on the analytical results of the first step, we did the second step of investigation to obtain the optimal arrangement of the LED array, which can be applied to various high-power LED lighting systems. The arrangement of the long distance between LEDs results in low temperatures for individual LEDs. Nonetheless, the distance is compromised because the volume is limited for applications. The analytical results of the second step provide the optimal distance where the heat generated by individual LEDs does not interfere with each other. The individual LEDs should be controlled not to generate heat as much as degrades the optical performance, especially under low natural convection. Hence, we also investigated the effect of pulse width modulation (PWM) to reduce thermal effect, which degrades the optical performance of a LED module. And the appropriate control of the electrical energy to LEDs can reduce thermal effect, resulting in improved luminescent efficiency. Consequently, though the lighting consumes less electrical energy, it might provide comparable luminous flux.

Methodology

Thermal analysis on LEDs

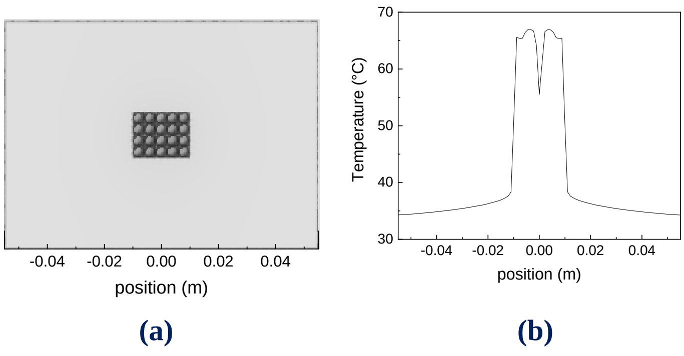
Heat generated from LEDs can effectively be dissipated through convection. A heat sink with a large contact area to the air must be employed to enhance the heat dissipation. Thermal energy transfer by thermal conduction is described as follows:

$$Q = \frac{kA}{L}(T_{\text{high}} - T_{\text{low}}) \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

where Q is thermal energy, k is thermal conductivity, A is area and L is the length, T_{high} is high temperature, T_{low} is low temperature. Maintaining the optimal operating conditions for LEDs is important to preserve their performance. Hence, the heat generated by the LED should be rapidly transferred to the heat sink. High-power LED lighting consists of numerous LEDs and individual LED has its own thermal distribution. When they are placed close to each other, the generated heat can be accumulated, resulting in degradation of LED lighting performance. On the contrary, placing individual LED farther apart can improve their performance although the size of their distribution may increase. Determining the thermal distribution of an LED can help find the optimal distance between LEDs. This investigation can be conducted in accordance with the heat equation, as follows [Petroski, 2003]:

$$\rho c_\rho \left[\frac{\partial T}{\partial t} + \vec{v} \cdot \vec{\nabla} T\right] = \vec{\nabla} \cdot \left(k \vec{\nabla} T\right) - \frac{2}{3}\mu\left(\vec{\nabla} \cdot \vec{v}\right)^2 + 2\left(\mu \vec{S} : \vec{S}\right) + \beta T \frac{\partial p}{\partial t} + \left(\vec{v} \cdot \vec{\nabla}\right) p + \mathrm{Q} \quad \text{……….(2)}$$

where ρ is density, $\vec{v}$ is velocity vector, p is pressure, t is time, μ is viscosity, k is thermal conductivity, S is strain rate tensor, T is temperature, β is expansion coefficient, Q is heat flux and $\vec{S}:\vec{S}=\sum_{j=1}^{3}\sum_{i=1}^{3}\vec{S}_{ij}\vec{S}_{ij}$. In the case of an ideal gas, βT can be assumed to be 1 and can be ignored because the viscosity μ for air is very small. In addition, in natural convection, air can be assumed incompressible. The temperature distribution of LED array with various distances between LEDs is depicted in Fig. 1. Figure 1(a) shows the temperature distribution of an LED array with closely arranged individual LEDs. Due to the interference of heat generated by these closely arranged LEDs, heat accumulates at the center of the array, leading to elevated temperatures that can negatively influence optical performance. In order to address this issue, the distance between LEDs can be increased, as shown in Fig. 1(c), leading to a substantial reduction in the averaged temperature as shown in Fig. 1(d). However, this approach results in a larger and bulkier system. Figure 1(e) shows the temperature distribution with optimal distance between LEDs. Despite the significant reduction in the distance between LEDs, the high temperature is almost similar to that of Fig. 1(d). The heat generated by individual LEDs still interferes with each other, which is negligible. By arranging LEDs at the optimal distance, the system becomes more compact, and exhibits minimized performance degradation due to thermal issues.



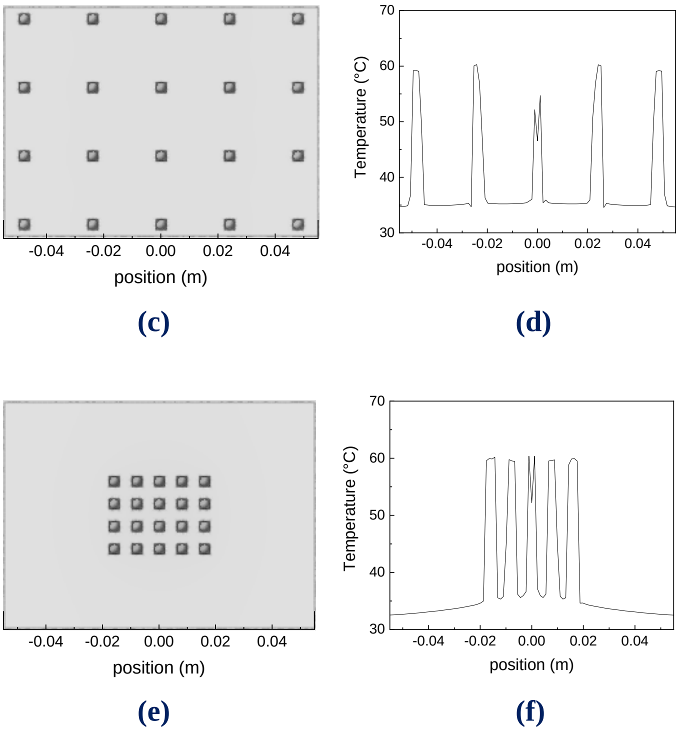


Figure 1. Thermal analysis results (a) temperature distribution of LED array with short distance between LEDs, (b) averaged temperature corresponding to (a), (c) temperature distribution of LED array with long distance between LEDs, (e) averaged temperature corresponding to (c), (e) temperature distribution of LED array with optimal distance between LEDs, (f) averaged temperature corresponding to (e).

Electrical power analysis on LED

While an LED is in operation, some of the consumed electrical energy transforms into heat. If this heat is not adequately dissipated, it can lead to performance degradation. Heat power of the LED is described as follows:

$$P_H = \left(1 - \frac{P_0}{I_F \cdot V_F}\right) \cdot P_e \quad \text{………………………… (3)}$$

where P_H is heat power, P_0 is optical power, I_F is forward current, V_F is forward voltage, and P_e is electrical power. After reaching a steady-state, high temperature in the LED can cause severe damage. To prevent this situation, PWM mode operation method can be employed. In PWM mode operation, the LED is turned on when PWM signal is applied, and temperature decreases while the LED is turned off. In this case, the luminance efficiency increases, though the averaged power decreases. Therefore, maintaining the adequate PWM mode operation may help preserve the performance of the LED lighting. The operating condition is described as follows:

$$\gamma = \frac{W}{T} \quad \text{………………………… (4)}$$

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where γ is ratio of on-state time to the period of a pulse, W represents the duration which PWM signal is in on-sate, and T represents the period of a PWM pulse.

Result and Discussion

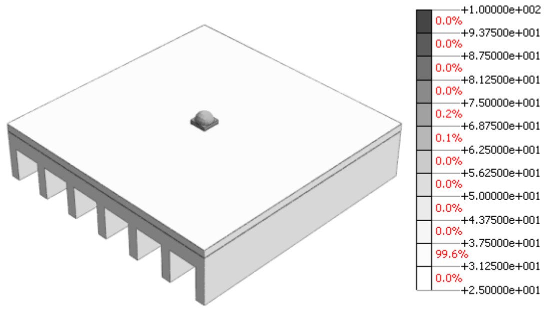
It is essential to investigate the thermal distribution of heat generated by an LED to establish the optimal distance between LEDs. Therefore, a thermal analysis is conducted using a simulation model that includes an LED, a metal core printed circuit board (MCPCB), and a heat sink. The material parameters are provided in Table 1. LED consists of two parts: a lens made of polymethyl methacrylate (PMMA) and a silicon (Si) body. The MCPCB consists of two layers, FR4 and aluminum (Al). The LED is soldered with lead to attach it to the MCPCB. A heat sink made of Al and a thermal interface material (TIM) is inserted between the MCPCB and the TIM to increase thermal transfer (Bouknadel et al., 2014; Tsai et al., 2012; Wu et al., 2012).

Table 1. Material parameters for a simulation model

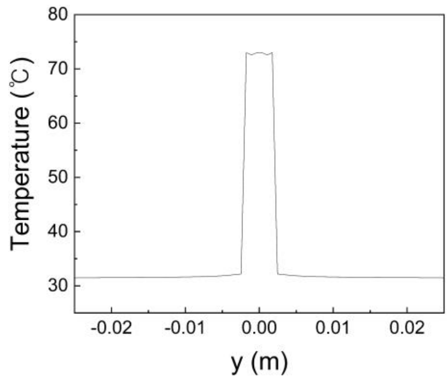
Material	Mass density (kg/m^3)	Thermal conductivity (W/mK)	Specific heat (J/kgK)
Polymethyl methacrylate (PMMA)	1190	0.21	1460
Lead	11,000	35	130
Silicon (Si)	2330	160	692
FR4	1850	0.35	1150
Aluminum (Al)	2700	230	890
Thermal Interface Materials (TIM)	2500	8.5	560

In the simulation, the LED's width and length are 3.5 mm. Heat sink has a width and length of 50 mm and a fin thickness of 7 mm. The thickness of the lead, the FR4 and the TIM is 0.1 mm. The LED's electrical power and heat power are 2.3 W and 1.38 W, respectively. The result of the thermal analysis is shown in Fig. 2. Figure 2(a) and (b) illustrate the Simulated temperature distribution and the temperature distribution at the center of the top surface of MCPCB, respectively. The highest temperature appears to be 72.3 ℃. Aside from the center of the LED, the temperature drastically decreased.

To determine the optimal distance between LEDs, we consider the case where numerous LEDs are placed closely together, potentially causing interference from the heat generated by each LED. The minimum distance for optimal placement should be longer than the distance at which the temperature reaches e^{-2} of maximum temperature. Suppose that two LEDs are arranged at this distance, thermal interference is negligible. In the simulation, this distance was 3.5 mm, corresponding to the LED's width and length.



(a)



(b)

Figure 2. Thermal analysis results. (a) Simulated temperature distribution and (b) the temperature distribution at the center of the top surface of MCPCB.

In this paper, the LED lighting consists of 20 LEDs, consuming 50 W of electrical power. Both the junction temperature and the minimum temperature were investigated. A junction temperature is assumed to be the highest temperature in an area of the MCPCB that is in contact with the LED. Since the minimum distance was assumed to be 3.5 mm in the single LED investigation, we have selected 4 mm as the minimum distance. MCPCB has a width and length of 80 and 110 mm, respectively. Subsequently, this distance increases in 4 mm intervals, reaching a maximum of 24 mm. Figure 3 shows the thermal analysis results of the LED lighting comprised of 20 LEDs. Figure 3(a) shows the simulated temperature distribution of the LED lighting with a 4 mm distance between LEDs. The ratio between the temperatures, 62.5 ℃ and 66.7 ℃, is 2.7%. However, when the distance between LEDs is increased to 24 mm, this ratio is reduced to 0, as shown in Fig. 3(b). Figure 3(c) illustrates the variations of junction temperature and minimum temperature with respect to the distance

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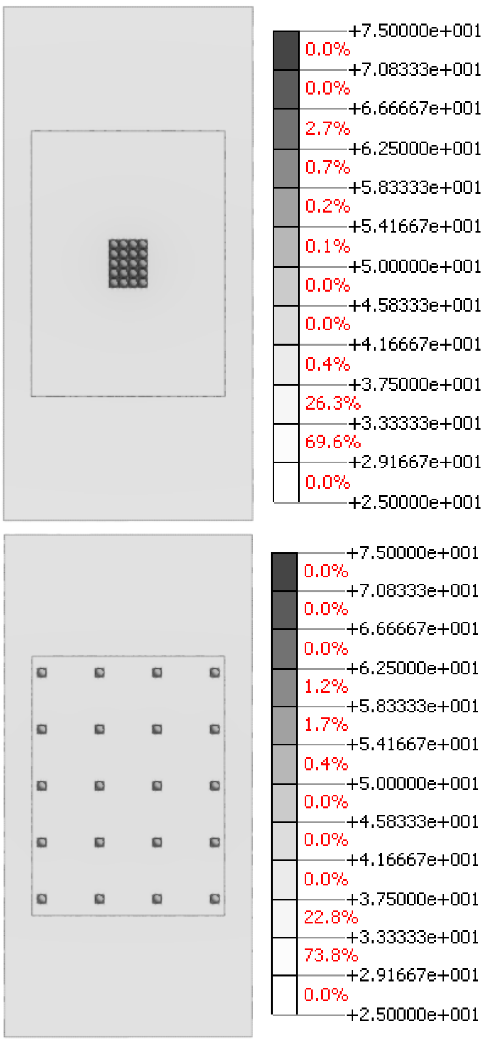
between LEDs. The Maximum temperature is 65.1 °C at a distance 4 mm. When the distance is 8 mm, the maximum temperature is 60.4 °C of which is reduced by 7.2% compared to that at a distance of 4 mm. At a distance of 12 mm, the maximum temperature is 60.1 °C, which is reduced by 0.5% compared to that at a distance of 8 mm. The maximum temperature does not decrease rapidly as the distance increases. It can be assumed that the optimal distance is approximately twice the minimum distance. When the distance between LEDs is 24 mm, the maximum temperature is 58.7 °C. Minimum temperature varies from 32.5 °C to 31.7 °C as the distance increases from 4 mm to 24 mm. There is no noticeable change in temperature. With LEDs positioned at the optimal distance, the board size can be reduced to dimensions of 36 mm in width and 46 mm in length. This investigation demonstrates that an LED lighting system can be designed to be compact while also effectively mitigating performance degradation caused by thermal issues.



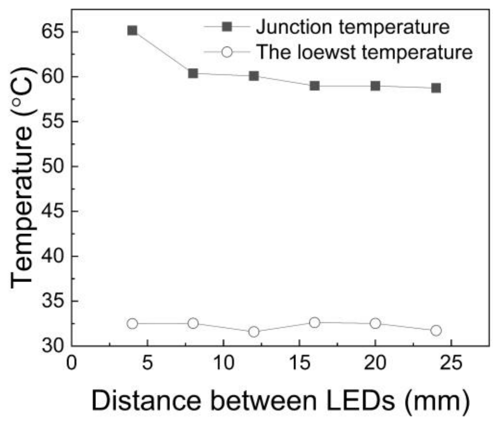


Figure 3. Thermal analysis for determining optimal distance. Simulated temperature distribution when the distance between LEDs is (a) 4 mm and (b) 24 mm. (c) the junction temperature and the lowest temperature.

Insufficient dissipation of heat generated by the LED lighting leads to severe damage, including significantly reduced lifetime, deterioration of luminance efficiency, and instability of peak wavelength. These issues are further exacerbated by low natural convection. Hence, the PWM is employed to maintain the proper operating condition in the LED lighting, resulting in enhanced luminance efficiency. This improvement is associated with the length of the off-time period. Frequencies of 60 Hz, 200 Hz, and 500 Hz were tested, with durations chosen at 0.2, 0.4, 0.8, and 1. A duration of 1 corresponds to continuous wave operation. Due to the moderate PWM frequency, the rectangular pulse was generated using a commercially available signal generator. A commercially available metal-oxide-semiconductor field-effect transistor (MOSFET) regulated the on-off status. The luminous flux was measured using a dispersive spectrometer, coupled with an integrating sphere of 0.5 mm diameter, to calculate the luminance efficiency. Concurrently, the electrical power was also precisely monitored.

Figure 4 shows the variation of luminance efficiency with different operating conditions as given by Eq. (4). In the continuous wave operation, luminance efficiency is 114.8 lm/W. In the PWM operation at 60 Hz, luminance efficiency is increased to 126.8 lm/W, providing 10.0% improvement compared to continuous wave operation. At 200 Hz, PWM operation results in a luminance efficiency of 118.5 lm/W, which is 3.1% improvement over continuous wave operation, and at 500 Hz, it increases to 117.3 lm/W, which is 2.1% improvement compared to continuous wave operation. As the operating condition decreases, the LED lighting consumes less electrical energy, resulting in improved luminance efficiency. This

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improvement is expected due to reduced temperature during PWM operation.

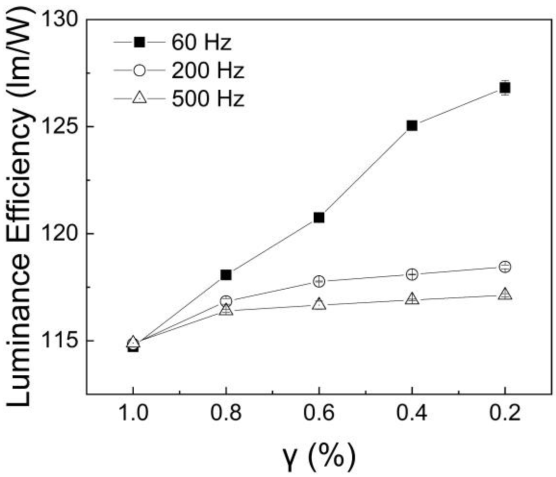

Figure 4. Luminance efficiency over ratio.

While the LED is not operating during off state of the PWM, its temperature decreases, improving luminance efficiency. Figure 5 shows luminance efficiency over relaxation time. The relaxation time represents the duration during which the LED is not operating. As expected, luminance efficiency is increased while the relaxation time is increased. The highest luminance efficiency is 126.8 lm/W with a relaxation time of 0.013 s.

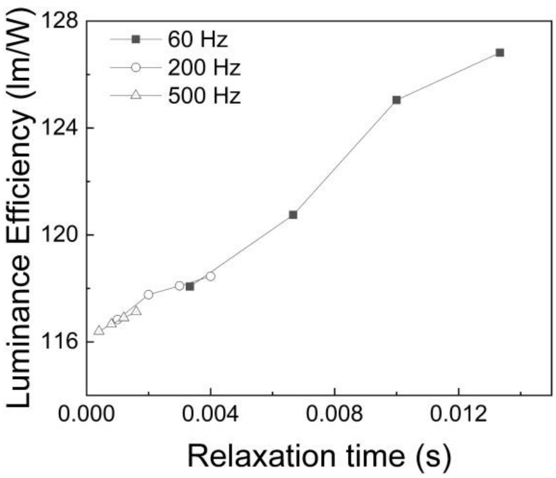

Figure 5. Luminance efficiency over ratio

Conclusion

In this paper, a 50 W LED lighting system has been developed. Two optimization approaches have been proposed to mitigate performance deterioration. A typical LED lighting system consists of numerous LEDs. A junction temperature is dependent on the distance between LEDs. However, the temperature does not linearly decrease as the distance increases. By arranging LEDs at this calculated optimal distance, it is possible to minimize performance degradation caused by thermal issues. Consequently, this arrangement enables a more compact system design, facilitating the development of a cost-effective lighting system. Nonetheless, this investigation was conducted using fixed sizes of aluminum layers such as heatsinks, which are critical in heat transfer. Interpreting these results with respect to the layers' varying characteristics is an area for future research. During continuous operation, the LED lighting reaches high temperatures in a steady state, which can lead to severe damage. To prevent this drawback, PWM operation is employed. Luminance efficiency is discussed with respect to relaxation time. As relaxation time increases, luminance efficiency is improved. However, it needs to be considered with luminescence flux. Those approaches are expected to enhance the stability and performance of LED lighting systems.

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Conflict of Interest

The authors declare no conflict of interest.

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