An optimized method of thermoelectric cooler-based thermal management for improving the luminous efficacy of light-emitting diodes

Quang-Khoi Nguyen*[1,2]

[1]*Faculty of Physics and Engineering Physics, VNUHCM-University of Science, Hochiminh City, Vietnam*
[2]*Vietnam National University Hochiminh City, Hochiminh City, Vietnam*

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Abstract—We experimentally performed a method of active cooling for a white LED that can reduce the temperature of the LED by using TEC to lower the temperature of the LED board. The relation of the LED board and input power for TEC was investigated to determine the optimized curve of the LED board temperature and input power for TEC. Also, the TEC-based cooling system was applied to RGBW LEDs. The result is meaningful in LED thermal management, improving the lighting quality and increasing the lifespan for both middle and high-power LED types.

Light-emitting diode (LED) solid-state lighting has been developed rapidly and used widely due to its unique properties, such as energy saving, high color rendering index, quick response, and long lifetime [1–3]. The limitation of the conversion process from input electrical power to output optical power, however, so there is a large part of electrical power is converted into heat [4–5]. Thus, it raises the temperature of the device and possibly causes the appearance of a heat problem, which is an unwanted phenomenon when the device is operated. Some of the results of heat problems are causing thermal decay for luminous flux and shortening the lifetimes; even overheating can cause damage to the mechanical, physical, and chemical properties of the structure of the device [6–7]. Thus, the target of reducing the effect of heat has attracted a lot of attention from researchers and engineers to propose solutions for thermal management effectively [8–11]. Among those solutions, a thermoelectric cooler (TEC) based thermal management is a potential solution to improve the performance of LED devices because of the quick cooling performance [12–13]. However, some gaps still need further study to optimize cooling efficiency when using TEC. The optimized method to simultaneously perform the highest cooling efficiency while using the lowest or most reasonable electrical power consumption has still not been reported.

This paper proposes and demonstrates an optimized method for improving LED performance using the TEC component. An optimized curve is determined, which shows the lowest achievable temperature for the LED board and the corresponding electrical power. Thus, the input electrical power for TEC can be optimized to avoid energy waste and achieve the best cooling efficiency. This TEC-based thermal management system is applied for high power Red Green Blue White (RGBW) LEDs.

The principle for achieving the best cooling performance and saving energy consumption is based on two main considerations, including the way of connection and finding out the optimized curve. Firstly, the diagram connection for the cooling system includes an LED matrix, TEC device, and aluminium heatsink structure, as shown in Fig. 1. The LED matrix is set to contact the cold end, and the heatsink is set to contact the hot end. When the system is powered, the heat produced by LEDs to the LED matrix is absorbed actively by the TEC cold end, transferred to the TEC hot end, and then dissipated through the heatsink. The more heat is transferred to the heatsink from the LED board, the lower the temperature of the LED matrix will be. Thus, the negative effect of heat on the White LED luminous efficacy will be reduced. Secondly, the determination of an optimized curve showing the LED matrix's lowest achievable temperature must be conducted and considered. Besides the electrical power injected into the LED, using the TEC device will cause more power consumption. Thus, optimizing the TEC input power is necessary to avoid the waste of energy consumption while still having high cooling performance. An optimized curve that shows the relation of LED board temperature as a function of electrical input power for TEC devices needs to be investigated and defined to gain this target. Based on this optimized curve, the level of electrical power consumption can be decided so that the corresponding best cooling performance can be achieved.

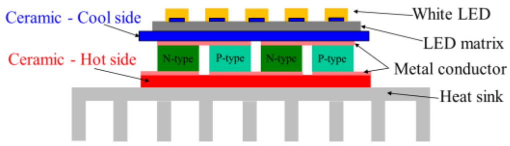

Fig.1. Illustration of connection for the cooling structure of the LED matrix/TEC/heat sink.

Figure 2 shows the photo of the main components used in the experiment.

* E-mail: nqkhoi@hcmus.edu.vn

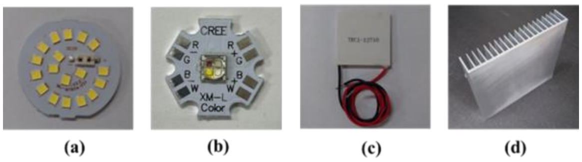

Fig. 2. The main components used in the experiment. (a) LED matrix; (b) RGBW LED; (c) TEC device; and (d) Aluminum heatsink.

Figure 3 shows the experimental setup for determining the optimized curve of LED board temperature versus input power for TEC. The connection is similar to the illustration shown in Fig. 1. The temperature of the LED matrix is detected by thermal couple type T that is connected to the instrument PicoLog TC-08 and controlled by the software in the computer.

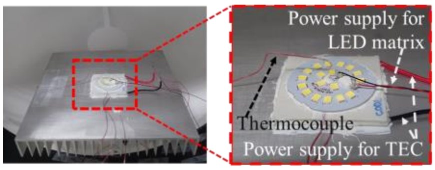

Fig. 3. Experiment setup for determination of optimized curve of LED matrix temperature versus input power for TEC.

Figure 4 shows the setup for the experiment of application for improving the performance of RGBW LEDs. The system is placed inside the integrating sphere system to measure the optical properties of output light. The RGB LEDs are driven by the setting in the integrating sphere system. The optical properties of output light were measured through the mode of long-term testing measurement that was an available function of the integrating sphere system. The TEC device is connected to the outside power supply, which can control the input power for TEC.

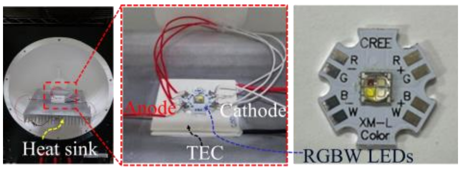

Fig. 4. Set up for experiment of application for improving the performance of RGBW LEDs.

Different electrical input power for TEC is driven to understand the cooling performance of the TEC1-12710 device. The corresponding temperature value and temperature distribution of the TEC cool surface is recorded as shown in Fig. 5. The temperature distribution in the cool surface of TEC was detected by the thermal camera corresponding to each input power value for TEC. The result shows the uniformity of temperature distribution on the entire cool surface of TEC. This uniformity of temperature distribution indicated the good characteristics of TEC in cooling applications. Figure 5(n) shows the temperature of the TEC cool surface corresponding to different input power, shown in Figs. 5(a) to 5(m). The utilized input powers are 0.1 W, 0.4 W, 0.89 W, 1.56 W, 2.42 W, 3.45 W, 4.65 W, 6.02 W, 7.56 W, 9.24 W, 11.17 W and 14.14 W, respectively, the correspondent temperature of TEC cool surface are 19.4 ºC, 16.1 ºC, 12.8 ºC, 9.5 ºC, 6.2 ºC, 3.8 ºC, 1.8 ºC, 0.1 ºC, –2 ºC, –3.4 ºC, –4.7 ºC, –6.1 ºC, respectively. From the investigation results, the behavior of temperature of the TEC cool surface with the input power showed that the higher the input power was, the lower the temperature of the TEC cool surface was.

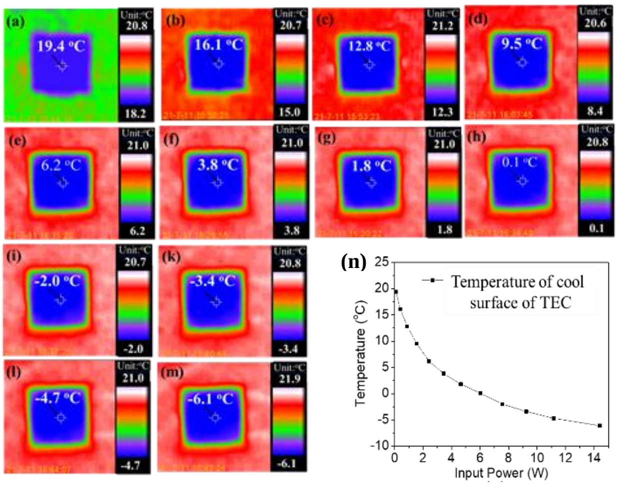

Fig. 5. (a)–(m) Temperature distribution of TEC cool surface is a function of input power for TEC; (n) Changing of the temperature of TEC cool surface versus input power for TEC.

To have the best performance in cooling and electrical energy saving, it is necessary to find the optimized curve of LED board temperature with different input power for TEC. The white LED board circuit was driven at a constant injection electrical current of 50 mA in all experiments. At the same time, different TEC input powers were utilized, which varied in ranges from 0 W to 21.95 W. Corresponding to each experiment, the value of temperature behavior was recorded in real-time from the initial state to the thermal steady state. Also, the behavior of LED board temperature at thermal steady state versus input power for TEC is determined to obtain the optimized curve. Figure 6(a) shows the change in the temperature of the LED board versus the time. When TEC is driven, the temperature of LED is decreased to the corresponding lowest temperature value, then increases gradually until reaching the steady state. Although using higher input power for TEC, at the initial stage, the temperature of the LED board can be reduced to a lower minimum value quickly, and some cases showed a higher temperature value at a thermal steady-state. This is caused by the joule heating effect of TEC when using higher input power (or higher driven electrical current for TEC), which is more serious. When the generated heat from TEC cannot be dissipated far from the hot end of TEC, it will cause a significant effect on the temperature of the LED board at a steady thermal state. Thus, it is clear that the input power for TEC is an essential factor in gaining an efficient cooling performance for the overall system.

The most crucial factor in evaluating the cooling performance is the temperature of the LED matrix at a thermal steady state. The better the cooling performance for the LED board, the lower the LED matrix's temperature was. Figure 6 shows the temperature of the LED matrix at the thermal steady-state corresponding to different input power for TEC. This curve showed that the lowest temperature and corresponding input power are 29.8^{o}C and 4.92 W, respectively. This input power value can be the largest power that should be used to operate the TEC to achieve the lowest temperature for the LED matrix. Because of the tie relation of temperature for the LED matrix and junction temperature of the LED device, the decrease of the LED matrix temperature will help reduce the LED's junction temperature correspondently. As a result, the performance of LED devices will be improved, including increasing the lifetime, stabilizing the color performance, and reducing the thermal-induced decay for output radiant flux.

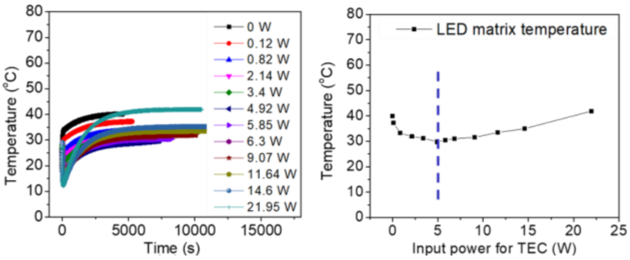

Fig. 6. The changing of the temperature of the LED matrix versus the time (left) and the changing of the temperature of the LED matrix at thermal steady state versus the input power for TEC (right).

After determining the optimized curve of LED board temperature versus the input power for TEC, the system is applied to improve the luminous efficacy of the RGBW LED device. The result when utilizing the input power for TEC of 4.4 W and 0 W is compared and was shown in Fig. 7. The result of the case using input power for TEC of 4.4 W showed that the thermal decay for output luminous flux is reduced as shown in Fig. 7. This is quite useful in lighting since it helps increase the luminous level of the light source and then increases the flux, which transfers to the illuminated target. Moreover, the shifting of peak emission of the blue, green, and red bands to longer wavelengths was prevented, as shown in Fig. 7. Once the shift of peak emission is controlled, the color performance for the output light will be stabilized. In addition, preventing the shifting of peak emission of blue, green, and red bands has shown the junction temperature in each LED was decreased when using the input power for TEC of 4.4 W. On the other hand, since there was a clear relationship between LED lifetime and LED junction temperature, this decreased LED junction temperature will help lengthen the lifetime of LED devices.

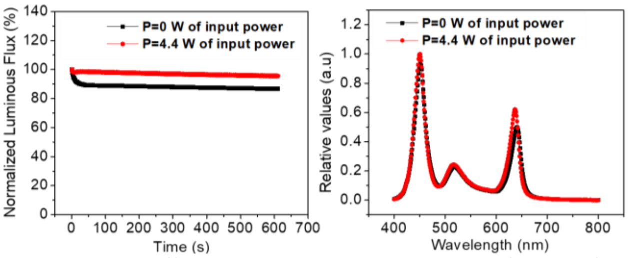

Figure 7. The difference between using the input power for TEC of 4.4 W and 0.00 W in terms of thermal-induced luminous decay (left) and spectral characteristics (right).

In conclusion, a thermoelectric cooler-based thermal management method was studied experimentally for improving the performance of light-emitting diodes. The relationship between the LED board and input power for TEC was investigated and optimized. This optimized curve of LED board temperature versus TEC input power showed that the lowest temperature can be achieved at 29.8^{o}C at a correspondent input power for TEC of 4.92 W. The result showed that this simple method helps gain the highest cooling performance while consuming reasonable electrical power. In an application, the TEC-based cooling system is applied to improve the performance of RGBW LEDs. The output spectrum of white light was increased while the color shift of emission peaks of blue, green, and red bands to a longer wavelength was prevented. The obtained result is valid when applied in the thermal management design for optoelectronic devices that require energy-saving and cooling performance.

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