Electro-thermal Collaborative Cooling with Delayed Power Rail Switching Auxiliary Charging by Considering Energy Harvesting Mechanism for High-power LEDs

Ning Wang, *Member, IEEE*, Zhi-Hao Shen, Cong Gao, Ming-Ming Chen, Can Ding, Guo-Rong Sui, Hong-Zhi Jia and Xiu-Min Gao

***Abstract*—With the development of high-power light-emitting diodes (LEDs), the heat flux density of devices has continued to increase, which in turn requires the development of increasingly effective methods of heat dissipation to control the working temperature of LEDs. Due to their impressive performance in solid refrigeration and energy harvesting, such thermoelectric devices as the thermoelectric cooler (TEC) and the thermoelectric generator (TEG) have been used to develop methods of heat dissipation that have been applied to power components and electronic devices. This paper proposes a delayed electro-thermal collaborative cooling system based on the TEC–TEG that uses the auxiliary charging technique for energy harvesting. In the designed delay circuit, two power source rails containing a TEG and a charged capacitor are switched automatically to supply energy to a TEC according to the charge of the capacitor and the discharge time of the delay circuit used for energy transmission. The results of experiments show that using our proposed scheme, the electromotive force can be increased by 21.6%, from 0.37 V to 0.45 V, in the TEG module compared with the collaborative electro-thermal cooling system without auto-delayed power rail switching. The switching time cost of the proposed system was only 0.8 s, and it could continuously supply enough electromotive force to drive the TEC and the overall cooling system. The proposed electro-thermal collaborative cooling system with delayed power rail switching and auxiliary charging can improve energy utilization and reduce device cost, which can help efficiently manage heat dissipation in high-power LEDs.**

***Index Terms*—power rail switching, auxiliary charging, electro-thermal collaborative cooling, energy harvesting.**

I. INTRODUCTION

Power light-emitting diodes (LEDs) are widely used in modern lighting owing to such excellent features as safety, low energy consumption, long service life, fast response, and environmental friendliness [1]. However, the electro-optical conversion efficiency of high-power LEDs is 20% and up to 80% of energy is released as heat [2]. The problem of heat dissipation restricts the development of high-power LEDs [3-6]. Because their light output is significantly influenced by the generated thermal energy, the luminous flux decreases and wavelength shift occurs if a large amount of heat is accumulated in the P-N junction in high-power LEDs. To ensure that they can operate normally, the junction temperature is not allowed to exceed 120 ℃ [7-8].

Hence, it is important to develop an effective heat dissipation method to solve the above problems [9-11]. Many methods are available to improve the heat dissipation capability of LEDs by lowering their junction temperature. A Cu nanoparticle paste was developed by Mou et al. to enhance the heat dissipation of LEDs [12], where the thermal resistance of the die-attach was reduced by 50% in comparison with the traditional die-attach layer. Xaviel et al. designed a heatsink based on a hollow aluminum cylinder with polymer axial fins [13]. This solution reduces the temperature of the LED junction by up to 18%. Shin et al. developed a heat sink with ionic wind to cool LEDs [14]. They used a high-voltage DC power supply to power the electrodes and ionize the surrounding air. Forced convected air results from the ionic wind owing to discharged gas. Experimental results showed that the temperature of the LED gradually dropped to 65 °C after 20 min as the ionic wind was purged on the heat sink. It was used in corona discharge to cool the LED by Wang et al. [15] to yield an approximate reduction of 34% in thermal resistance. Different liquid cooling blocks were experimentally and numerically investigated by Muhsin et al. [16]. From the results obtained using different cooling blocks, they were able to reduce the maximum temperature values by using thinner blocks, which also increased the mass flow rate. Yang et al. designed an LED liquid cooling system for streetlights with a micro-heat exchanger installed on top of the LED chip in bracket, and a micro-centrifugal pump installed at the bottom of the lamp holder. The micro-heat exchanger drove the cooling water to remove heat from the LED [17]. Nanofluid technology does help transport heat from devices efficiently [18]. Zhao et al. used nanofluidic heat pipes in a design to cool LED headlamps [19]. The results of tests showed that the distributed heat pipes yielded better cooling performance than linear heat pipes. The methods described above can lower the junction temperature of LEDs. Techniques

Manuscript received. This work was supported by the NSFC under Grant 61804096, the National Key Research and Development Plan--Earth Observation and Navigation Key Special Project under Grant 2017YFB0503102, and the National Key Research and Development Program of China under Grants 2018YFC1313803 and 2018YFA0701800. (Corresponding author: Can Ding)

The authors are with the Engineering Research Center of Optical Instrument and System, Ministry of Education, Shanghai Key Lab of Modern Optical System, University of Shanghai for Science and Technology, Shanghai, China.

C. Ding is with the Global Big Data Technologies Center, University of Technology Sydney, Sydney, NSW, Australia. (e-mail: can.ding@uts.edu.au).

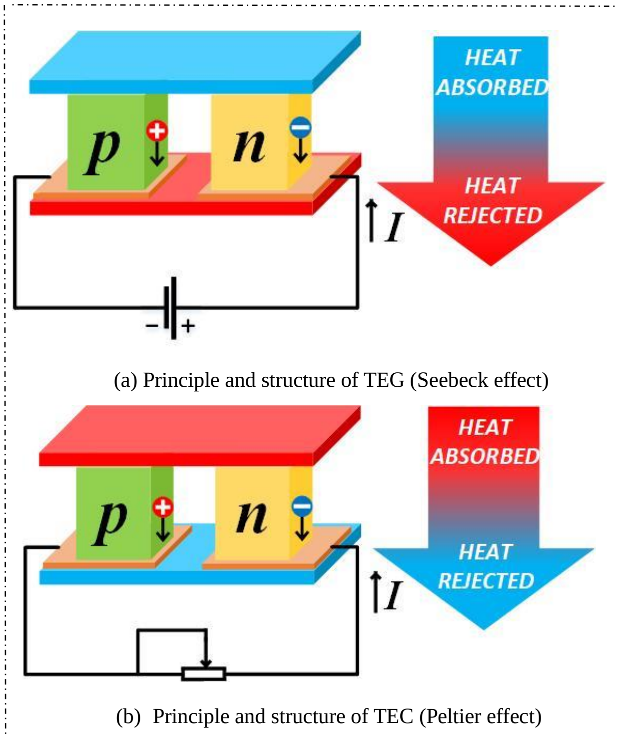


Fig. 1. (a) Principle and structure of TEG (Seebeck effect). (b) Principle and structure of TEC (Peltier effect).

of efficient heat dissipation in packaging are often employed to quickly transfer heat generated by the LED pedestal to the environment [20]. In particular for high-power LEDs with heat flux higher than 100 W/cm^2, methods of active cooling, such as air cooling, liquid cooling, heat pipes, and thermoelectric cooling, are used to reduce the junction temperature of chips [9, 21-25]. However, they are unsuitable because of their high cost, low stability, and complex structures. Of heat dissipation schemes, active cooling by using a thermoelectric cooler (TEC) has gradually emerged as the preferred one owing to its simple structure, small volume, lack of noise during operation, lack of pollution, easy packaging, and good controllability as shown in Fig. 1(a) [26]. Many studies have been conducted to solve the thermal problems in LED packaging. For example, Li et al. built an automated high-power LED temperature management system using a TEC, a micro-fan, and a micro-controller [27]. The system’s temperature can be automatically reduced in it, and the luminous efficiency of the LED can be improved by 12% at the controlled panel temperature using the TEC [28]. By using the TEC with PID control, Fredes et al. tested the optical performance of deep UV light-emitting diodes (UV-C LEDs) [29]. Their experimental results indicated that UV irradiation from light sources increased by 6% when the junction temperature was reduced from 59 °C to 44 °C. Although the TEC has many advantages in the heat management of high-power LEDs, it consumes a large amount of electric power with low conversion efficiency.

To further improve the efficiency of energy conversion and cooling capability of TEC cooling systems, auxiliary methods are used to reduce power dissipation in related work. By using additional cooling, David-Shiloah proposed a TEC-based thermal solution with auxiliary coolant channels embedded into the cold plate [30]. In experiments, a temperature drop of ~40 ℃ was observed at power load of 400 W without the footprint space constraint. Using combined auxiliary refrigeration, Wang et al. conducted experiments on the junction temperature and photoelectric characteristics of the output for air cooling + TEC and liquid cooling + TEC [26]. When the ambient temperature was high at 65 °C, the junction temperatures were 85.6 °C (air cooling + TEC) and 59.5 °C (liquid cooling + TEC), all lower than the upper limit of 120 °C. The corresponding output light was 1607.3 lm. To improve the thermal management of a high-power LED headlight, LED cooling through a thermoelectric cooler-integrated, water-cooled microchannel heat sink was investigated in an experiment [31]. The temperature of the LED was reduced to only 60 °C at different working conditions at an ambient temperature of 80 °C and a flow velocity of water of 0.49 m/s in the microchannel when the current across by the TEC was 2 A. These studies on auxiliary heat dissipation systems for the TEC have focused on cooling structures and combination modes, where the thermal energy released by the system cannot be harvested and utilized. To address this defect, the TEG as shown in Fig. 1(b) can be used to supply energy to the TEC, which can transform the thermal energy induced by temperature differences between LEDs and the environment into electricity based on the Seebeck effect. For example, an electro-thermal collaborative heat dissipation management was proposed in our previous work, where the TEG was used as auxiliary heat dissipation system for the TEC [32]. With the help of a voltage boost converter in this system, the harvested electrical power can be used to power a temperature sensor used to monitor the surface temperature of the high-power LED. Lin et al. proposed a combined TEC–TEG system where two single-stage TEGs were employed to separately power the hot and cold stages of the TEC [33]. As the tuned current supplied to the two stages flowed through the TEG–TEC system in a 30-couple arrangement, the cooling capacity was enhanced by 75% and the maximum temperature was 76.8%. Although some improvements have been made to the cooling capacity by using the TEG for auxiliary refrigeration, the time of approach of auxiliary refrigeration has not been considered. No automatic power management mechanism has been involved in the energy collection cooling systems either.

In this paper, a collaborative electro-thermal cooling scheme with delayed power rail switching and auxiliary charging mode is proposed based on an energy harvesting mechanism using the TEG, for the first time in the literature. The TEC is driven by energy transformed from heat released by high-power LEDs to cool the entire system based on effective thermal management. Compared with the traditional cooling method, this scheme consumes less energy to achieve the predicted cooling effect due to the mechanisms of delayed power rail switching and auxiliary charging, which is its main advantage and innovation. In an experiment, a maximum of 45 mW of energy was saved by the proposed method. The proposed electro-thermal collaborative cooling system with delayed power rail switching and auxiliary charging can also improve energy utilization and lower device cost. The experimental results show that the electromotive force increased by 21.6%, from 0.37 V to 0.45 V, and energy efficiency improved by 5%, from 23% to 24.15%, using the proposed method. The proposed power rail switching and auxiliary charging circuit occupies only a small area, and can be integrated with a constant current-driving power circuit inside the LED and packaged in the body of its lamp. In addition, the TEC and TEG can be made very thin, hundreds of microns in height, and can be integrated with the LED substrate on demand. This scheme is thus feasible for use in LED packages. The experimental results show that high-power LEDs can be stabilized at normal operating temperature for a long time using the proposed method.

The remainder of this paper is organized as follows: By using delayed power rail switching and auxiliary charging, the collaborative electro-thermal heat dissipation system for high-power LEDs based on the TEC is detailed in Section II. In Section III, the performance of our scheme is compared with that of other cooling systems through experiments. Finally, the conclusions of this study are drawn in Section IV.

II. Heat Dissipation System For High-power LEDs

As mentioned above, TEC cooling has advantages over other methods of heat management for high-power LEDs. Therefore, we first consider a heat dissipation system that uses only TEC cooling. Based on this, a collaborative electro-thermal cooling system that combines the TEC and the TEG is designed to investigate the feasibility of its use for energy harvesting. Finally, we propose and test a delayed electro-thermal cooling system with power rail switching and auxiliary charging for high-power LEDs. Hence, the two schemes considered serve comparative purposes to assess the performance of the proposed cooling system.

A. TEC Cooling

The power consumption of high-power LEDs can be up to several or even tens of watts of energy, and the heat released by the device can be removed by the conventional TEC owing to its active and controllable cooling. As a comparable candidate, an experimental system is given in Fig. 2, where the TEC and a heat sink are used to dissipate heat generated by the LED. The cold side of the TEC is in indirect contact with the substrate of the LED chip while its hot side can release considerable heat into the periphery through the heat sink. However, this heat dissipation package is similar to a heat pump, and requires external power to supply electricity. Once the system is working normally, three high-precision thermocouple thermometers are used to track the thermal characteristics of different parts of the high-power LEDs and TEC devices in real time. T_{LED} (the surface temperature of the LED), T_{CC} (the temperature of the contact surface between the LED and the TEC), and T_{CH} (the contact surface temperature between the TEC and the bottom of heat sink) were measured by the thermocouple thermometers.

B. Collaborative Electro-thermal Cooling

Because TECs are energy-consuming devices while TEGs are energy-generating devices, it is interesting to study ways to combine them for the thermal management of LEDs. As shown in Fig. 3, for the entire experimental system considered here, the TEG was used, and was attached to the TEC. A heat sink was installed at the bottom of the TEC. The TEG served as energy conversation device and harvested electric energy owing to the difference in temperature between the LEDs and the TEC. The high-power LEDs generated heat that caused their temperature to rise. The TEC caused temperature to drop at the bottom of the TEG in the meanwhile. Hence, thermal energy could be converted into electrical energy as a result of the large temperature difference between the sides of the TEG. In the experiments, two excitation sources (V_{LED} = 10 V, V_{TEC} = 5 V) at both ends of the LED and the TEC were applied. Finally, the contact surface temperature between the LED and the TEG was measured by the thermocouple thermometers, in addition to T_{CC}, T_{LED}, and T_{CH}.

C. Delayed Collaborative Electro-thermal Cooling with Power Rail Switching and Auxiliary Charging

In the collaborative electro-thermal cooling system shown in Fig. 3, although electrical energy is produced, it is not used to drive a circuit. To improve the efficiency of energy conversion by recycling and reusing it, the experimental scheme with delayed power rail switching and auxiliary charging mode is shown in Fig. 4. The mechanism of the delayed power railway switching is based on the characteristics of the RC delay circuit and the working principle of the NAND gate. At the beginning of the operation of the LED, the small temperature difference between the environment and the LED is not enough to enable the TEGs to work. Hence, the same power supply V_{LED} for the LED is used to power the TEC controlled by an RC delay circuit. A resistor, a capacitor, and the electromotive force E

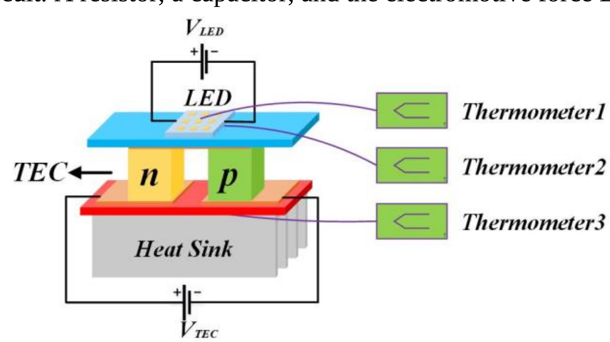


Fig. 2. Scheme of heat dissipation system for high-power LEDs using the TEC.

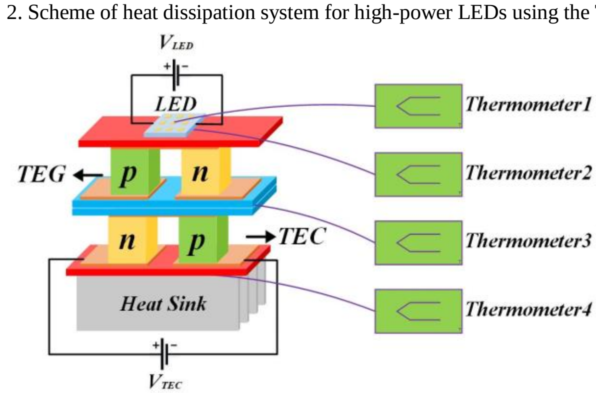


Fig. 3. Heat dissipation system for high-power LEDs based on collaborative electro-thermal cooling.

generated by the TEG are connected in series to form an active closed circuit. If the current passes through it, the electromotive force charges the capacitor through the circuit, and the resistance and voltage of the capacitor increase gradually. The NAND gate chip HD74LS00P is composed of four two-input NAND gate circuits, only one of which is used here. A 10-μF capacitor is connected to one input of the NAND gate to enable the delay switching circuit to work properly. Once the system is powered on, the measured charging delay is only 0.8 s. The power supplied to the TEC is then shut-off because one of the inputs of the NAND gate reaches a higher level while the other remains high. Once power to the delay circuit is disconnected, the capacitor starts discharging, which takes 53 s. When the capacitor is fully charged, the control circuit of the power supply shuts off automatically. As a result, the power supply to the TEC is switched off. Before this, the difference in temperature between the normally operating LED and TEC was sufficient to drive the operation of the TEG. As a second rail power, all the power generated by the TEG was supplied to the TEC. A diode was connected in series with the TEG to prevent the current generated by it from reversing. After the completion of the above processes, the proposed collaborative electro-thermal cooling system enters the normal working mode. Compared with the second power state, we can call the first booting stage the auxiliary charging mode, when the TEC is driven only by an external power source. The power rail switching was started and the electric energy converted by TEG was supplied from DC module to TEC through this auxiliary charging mode. Therefore, it is not necessary to apply an additional source of power excitation to the TEC because the electricity generated by it can supply enough energy to drive the TEC for a while. T_{GH} (the contact surface temperature between the LED and the TEG), and T_{GC} (the contact surface temperature between the TEG and the TEC) were measured by thermocouple thermometers. When the discharging electric capacity of the capacitor was not sufficient to drive the NAND gate, the channel for external power V_{LED} was opened to supply power to the TEC for its continued operation. Therefore, the power rail switching time can be controlled by adjusting the charging capacitance.

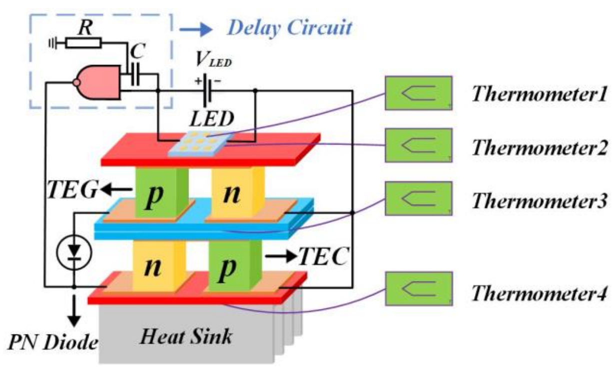


Fig. 4. Delayed collaborative electro-thermal cooling with power rail switching and auxiliary charging.

TABLE I
PARAMETERS OF HIGH-POWER LEDS.

Model	GP-H030
Chip Size (mm^2)	0.762×0.0762
Operating Voltage (V)	9-11
Current (mA)	760
Product Size (mm^2)	20×29
Package Structure	COB
Optical Efficiency (lm/W)	100
Lifespan (hour)	35000
Color Temperature (K)	White light 3000-3500

III. COLLABORATIVE COOLING MODELS

The main components of cooling systems for high-power LEDs are a high-power integrated LED lamp, an aluminum heat sink, DC power supplies, thermocouple thermometers, multimeters, a capacitor, a diode, and a dual-in-line chip. According to requirements of the testing environment, the thermoelectric generator and the thermoelectric cooler used were SP1848-27145 and TEC1-12705, respectively. The LED model used in the experiment was the GP-H030, and its parameters are shown in Table I. The packaging structure of the LED module in the experiment was based on the COB (chips-on-board) package. The COB package can directly package multiple chips in an MCPCB (metal core PCB), which allows for high-power LEDs to dissipate heat directly through the substrate. During the operation of the LEDs, the efficiency of electro-optical conversion cannot reach 100%. It is impossible for all photons generated inside to be emitted to the outside of the chip. This part of the energy is converted into thermal energy, which ultimately leads to a rise in temperature. The LED is coated with a phosphor layer, because of which the thermocouple cannot measure the temperature of its chip directly. However, LEDs are directly encapsulated on the metal plate. Owing to the low thermal resistance, the temperature of the LED can be obtained indirectly by measuring the metal plate surface with a thermocouple. A photograph of the way to measure the interface temperature by thermocouple is shown in Fig. 5.

Four thermocouples were used to measure the temperature as shown in Fig. 4. T_{LED} (the surface temperature of the LED), T_{GH} (the contact surface temperature between the LED and the TEG), T_{GC} (the contact surface temperature between the TEG and the TEC), and T_{CH} (the contact surface temperature between the TEC and the bottom of the heat sink) were measured. The model of thermocouple thermometer used in the experiments was AT4708, with an accuracy of ± 0.2% and resolution ratio of 0.1 ℃. When a power source of 10 V was supplied to the high-power LEDs without any heat dissipation system in place, the electrical current across all LEDs was 0.9 A. The operating power of the LEDs was $P=V_{LED}\times I_{LED}$=10 V×0.9 A=9 W each. From the beginning, T_{LED} was measured and recorded every 30 s. According to the results, the transient behavior of values of T_{LED} is shown in Fig. 6. The experimental data show that the surface temperature of the LEDs rose rapidly when they began operating. However, their temperature became stable at around 160 ℃ after 8 min. The working temperature far exceeded the rated operating temperature of the LEDs of 120 ℃, which incurs the risk of them burning. Therefore, it is desirable to employ an effective heat dissipation device for high-power LEDs during operation.

A. LED Heat Dissipation System Using TEC

To avoid the risk mentioned above, the TEC is employed to cool the junction temperature of the high-power LEDs, as illustrated in Fig. 2. Data related to the cooling effect of the dissipation system were obtained by measuring TLED, TCC, and TCH at intervals of 30 s. Once the TEC module had been energized for 3 min, TLED was stabilized at 30 ℃ using this cooling scheme, where the obtained temperature data are plotted in Fig. 6. Compared with the system without any heat dissipation device, the junction temperature of each LED was significantly reduced from 160 ℃ to 30 ℃, which ensured that they operated within a reasonable and safe range of temperature. A temperature difference of approximately 25 ℃ was generated between sides of the TEC, as measured once it had been powered on for over 10 min. From the perspective of heat management, the TEC has the advantages of a clear cooling effect and easy integration. However, the proposed heat dissipation system using it requires an additional power source for the TEC module, which might lead to high energy consumption.

B. Collaborative Electro-thermal Cooling System for LEDs

In the collaborative electro-thermal cooling system, a large amount of heat, resulting in a high temperature of the surroundings, is released from high-power LEDs, with a low-temperature environment developed by the TEC attached to the bottom of the TEG. The TEG is used here to convert thermal energy into electricity based on the large temperature difference. A heat dissipation system based on collaborative electro-thermal cooling is built as shown in Fig. 3, where the temperature data at each contact point were as given in Fig. 7(a), and the output voltages of the TEG at different moments are plotted in Fig. 7(b). The experimental results showed that the T_{LED} decreased significantly and stabilized at 45 ℃ after the cooling system had been energized for 3 min. Thus, part of the heat released by the high-power LEDs was absorbed by the TEG as the difference between T_{LED} and T_{GH} was in the range of 1 ℃ to 2 ℃, whereas the temperature of the collaborative electro-thermal cooling system remained constant, as shown in Fig. 7. About 0.37 V of electromotive force was produced by the TEG once the system had entered a steady state as shown in Fig. 8.

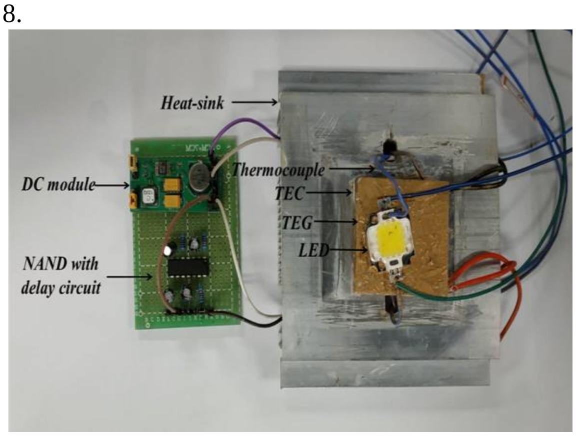


Fig. 5. Photograph of the entire system.

Although part of the energy characterized by the electromotive force was generated by energy harvested by the TEG, the converted electrical energy was not used efficiently. Moreover, the cooling effect of the collaborative system was not as good as that of a single TEC cooling system from the perspective of thermal management. In terms of energy consumption, additional power was still needed for TECs in the collaborative system. Hence, an automated heat dissipation system based on energy harvesting for high-power LEDs is needed.

C. Electro-thermal Collaborative Cooling System with Delayed Power Rail Switching and Auxiliary Charging

To solve the problem of the reuse of electric energy in the proposed system, a delayed circuit was constructed consisting of a NAND gate chip, a resistance and a capacitor. The NAND gate chip HD74LS00P was composed of four two-input NAND gate circuits, only one of which was used. A 10-μF capacitor was connected to one input of the NAND gate for the normal operation of the delay switching circuit. Once the proposed system was powered on, the measured charging delay was only0.8 s. The power supplied to the TEC was shut-off as the one input of the NAND gate reached a high level while the other remained high. Once power to the delay circuit had been disconnected, the capacitor began discharging, which took 53 s.

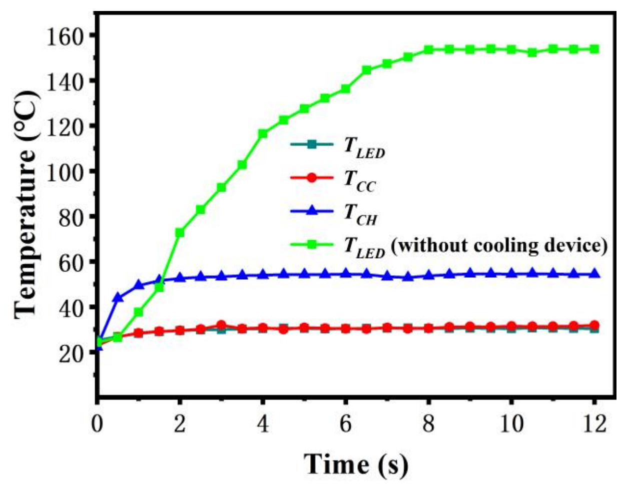


Fig. 6. Dependence of each test point on temperature over time in the heat-dissipation system for the TEC.

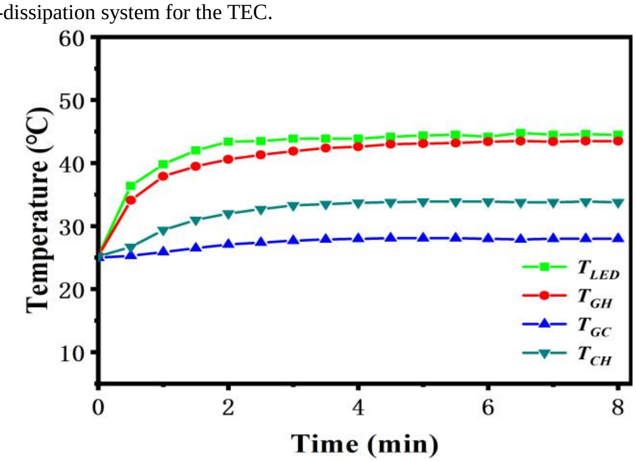


Fig. 7. Dependence of each test point on temperature over time in the collaborative cooling system.

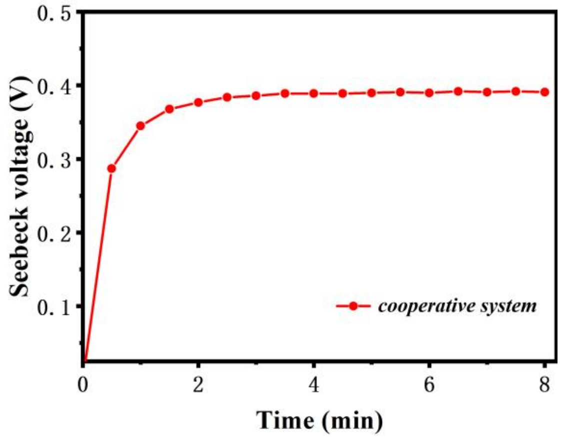


Fig. 8. Transient characteristic of temperature-dependent electromotive force generated by the thermoelectric collaborative cooling system.

By contrast, the very short charging time met the requirement of powering up the TEC using an external power supply in the early booting stage and then disconnecting from the DC power source. Following this, the power source driving the TEC was immediately switched to that for the TEG, owing to a sufficiently large temperature difference between the junction of the LED and the cold side of the TEC at the time, completing the process of automatic power rail switching. Then, the energy generated by the TEG was transferred to the DC boost module, which raised the voltage to 5 V and stably output it to the TEC. The maximum output power was 45 mW. Finally, the temperature of the proposed electro-thermal cooling system became stable once the high-power LEDs had been on for 4 min, and T_{LED} stabilized at 55 °C, as shown in Fig. 9. It can be concluded that this system was more effective at reducing the temperature of the high-power LEDs than one without a cooling structure. Moreover, the difference between T_{GH} and T_{LED} ranged from 5 °C to 6 °C, enabling the TEG to function in suitable surroundings by absorbing the heat induced by the high-power LEDs. On the other side, the transient change relationship for the electromotive force generated by the temperature difference, named the Seebeck voltage, is shown in Fig. 10. It took only 2 min to reach a stable output state for our proposed system, compared with 5 min for the collaborative system, while the electromotive force generated by the TEG increased by 21.6%, from 0.37 V to 0.45 V.

D. Performance Comparison

The effects of heat dissipation of four different schemes for high-power LEDs were compared in experiments. Table II shows the overall system results. According to them, the proposed scheme with delayed power rail switching and auxiliary charging mode for high power LEDs consumed the least energy, only 9 W, which was identical to that of an LED system without cooling but with the maximum T_{LED}. It is also clear a T_{LED} lower than 60 °C was achieved in three systems that used the TEC cooling structure. However, energy harvesting was not used in the LED+TEC scheme without a mechanism for power saving. Both the system for LED heat dissipation using the TEC and the collaborative electro-thermal cooling system needed to supply external energy to the TEC to maintain the operation of the LED in a stable state. Given that a low chip temperature is a primary requirement, the LED+TEC and LED+TEC+TEG techniques satisfied this. However, they required extra energy to drive the TEC. The thermal energy released by the LED was converted into electric energy, and the TEC was driven after delay processing in this work. Although some part of the electromotive force was generated using energy harvesting on the TEG in electro-thermal collaborative cooling system, the converted electrical energy was not used efficiently, and was insufficient to drive the TEC stably. The experimental results show that the cooling capacity of this scheme was not as good as that of the previous two schemes, namely the schemes of heat dissipation system using TEC and collaborative electro-thermal cooling system. electromotive force by 21.6% from 0.37 V to 0.45 V, generated by the TEG, compared with the collaborative force used to drive the TEC to cool the system using many TEG couples. Once it was working, no additional external energy supply was needed due to our energy reuse system, which saved a maximum power of 5%, and improved energy efficiency from 23% to 24.15%. The high-power LEDs, TEG, and TEC all acted as independent devices, and not as packaged together, which means that the thermal resistance between them was higher.

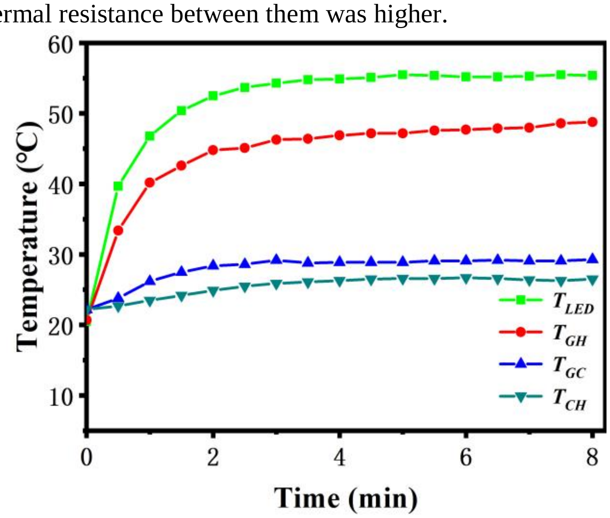


Fig. 9. Temperature of the proposed collaborative electro-thermal cooling system.

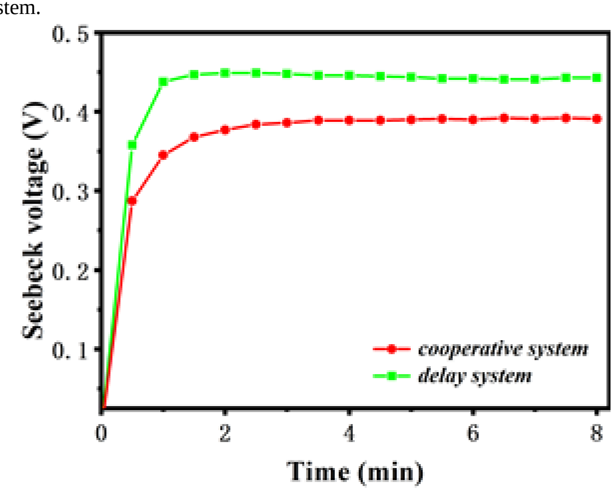
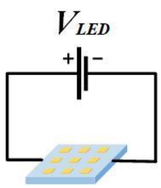
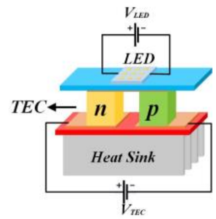
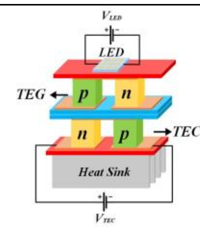
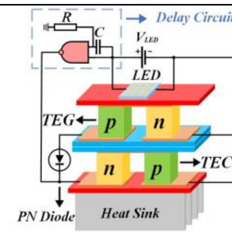


Fig. 10. Transient state characteristics of electromotive force in our proposed system.

TABLE II
Overall system performance characterization of four schemes.

Scheme	LED without Cooling	LED+TEC	LED+TEG+TEC	This work
Structure				
Stabilized T_{LED}	150 ℃	30 °C	45 °C	55 °C
Power rail switching Time	N/A	N/A	N/A	0.8 S
Power consumption	9W	9.06W	9.06W	9W
Seebeck voltage	N/A	N/A	0.37V	0.45V
Power saved	0	0	4.08%	5%
Time to stability	8 min	2 min	2 min	4 min

However, the experimental data confirmed that the proposed design caused the system to function normally and achieve the predicted effect. Compared with the scheme for the LEDs without a cooling system, the same amount of energy was consumed. The maximum power saved by the proposed method was 5%, 45 mW as measured by the multimeter. This was sufficient to drive the TEC. Considering heat dissipation management and energy utilization, the proposed method reduced the temperature of the high-power LED and contributed to the reuse of heat energy. The experimental results also show that the temperature of the high-power LED was stable in its normal range, mainly due to the refrigeration function of the TEC. The auto-delayed collaborative electro-thermal cooling system proposed in this paper thus provides a solution for the heat dissipation management of high-power LEDs.

IV. CONCLUSION

It is highly desirable to have an effective heat dissipation device for high-power LEDs during operation, as they otherwise risk burning. The TEC as an effective cooling device is widely used in illumination systems, but requires an additional power source. The feasibility of the proposed collaborative electro-thermal cooling scheme with delayed power rail switching and auxiliary charging mode was verified. It improved energy utilization to realize the effective thermal management of high-power LEDs. The experimental results show that the proposed scheme consumed the same amount of energy as that without a cooling system, but the temperature of the high-power LED dropped by over 65% due to the mechanism of delayed power rail switching that enabled the automatic charging of the TEC through the TEG. A maximum Seebeck voltage of 0.45 V was attained and 5% power was saved with a power rail switching time of 0.8 s. T_{LED} decreased to 55 ℃, and was stable in a normal range of operation. The TEG absorbed heat released by the high-power LED and transformed thermal energy into electricity to drive the TEC in the proposed cooling system. On the one hand, the refrigeration function of the TEC helped dissipate heat, and on the other, the TEG also helped release heat from the LED by benefiting from the Seebeck effect. The higher the power of the LEDs is, the more important is effective thermal management. For currently available integration technologies, lighting at higher power means that more LED chips need to be integrated, which increases the size of LED devices. In this experiment, the size of the LED was close to that of the TEG and the TEC. The proposed scheme also worked well in experiments using 3 W, 5 W, and 9 W LED modules, and thus is applicable to higher-power devices.

REFERENCES

[1] F. Loose, R. R. Duarte, C. H. Barriquello, M. A. Dalla Costa, L. Teixeira and A. Campos. “Ripple-based visible light communication technique for switched LED drivers”, *2017 IEEE Industry Applications Society Annual Meeting, Cincinnati*, OH, United State, Oct. 1-5 pp. 1-6, 2017

[2] N. Bădălan, P. Svasta and C. Marghescu. “A Method for Improving an Active Cooling Solution for LEDs”, *2018 IEEE 24th International Symposium for Design and Technology in Electronic Packaging (SIITME)*, *Iasi*, Romania, Oct 25-28. pp. 5-8, 2018

[3] Wang, C. P., Chen, T. T., Fu, H. K., Chang, T. L., and Chou, P. T. Transient analysis of partial thermal characteristics of multistructure power leds. *IEEE Transactions on Electron Devices, 60*(5), pp. 1668-1672. 2013

[4] Zhang, Y., Ding, M., Zhao, D., Huang, H., Huang, L., and Lin, Y., et al. Analysis and modeling of thermal-electric coupling effect of high-power monolithically integrated light-emitting diode. *IEEE Transactions on Electron Devices, 65*(2), pp. 564-571. 2018.

[5] Chen, H., Lin, S., and Xiong, C. Analysis and modeling of thermal effect and optical characteristic of led systems with parallel plate-fin heatsink. *IEEE Photonics Journal, 9*(2), pp. 1-11. 2017.

[6] Jian, W. M., Lee, B. K., and Devarajan, M. Thermal impedance measurement on different chip arrangements for various multichip leds application. *IEEE Transactions on Electron Devices, 62*(9), pp. 2906-2912. 2015

[7] Kaya, M. Experimental study on active cooling systems used for thermal management of high-power multichip light-emitting diodes. *The Scientific World Journal, 2014*, 563805. Aug., 2014.

[8] Baumgartner, H., Vaskuri, A., Kärhä, P., and Ikonen, E. A temperature controller for high power light emitting diodes based on resistive heating and liquid cooling. *Applied Thermal Engineering, 71*(1), pp. 317-323. 2014.

[9] Tamdoğan, E, and Arık, Mehmet. Natural convection immersion cooling with enhanced optical performance of light-emitting diode systems. *Acta Cytologica, 24*(1), 82. 2015.

[10] Chakravarthii, D. M. K., Devarajan, M., Suvindraj, K., and Choo, C. L. Thermal characterization of leds mounted on substrates with converging-diverging and diverging-converging channels. *IEEE Transactions on Electron Devices,64*(8), pp. 3308-3315. 2017.

[11] Wang, N., Li, X. C., and Mao, J. F. Improvement of thermal environment by thermoelectric coolers and numerical optimization of thermal performance. *IEEE Transactions on Electron Devices*, *62*(8), pp. 2579-2586. 2015.

[12] Y. Mou, H. Wang, Y. Peng, H. Cheng, Q. Sun and M. Chen. Enhanced Heat Dissipation of High-Power Light-Emitting Diodes by Cu Nanoparticle Paste. *IEEE Electron Device Letters, 40*(6), pp. 949-952, 2019

[13] M. Vaka, R. Walvekar, A. K. Rasheed, M. Khalid and H. Panchal, A Review: Emphasizing the Nanofluids Use in PV/T Systems. *IEEE Access,* vol. 8, pp. 58227-58249, 2020

[14] Dong, H. S., Baek, S. H., and Han, S. K. Development of heat sink with ionic wind for led cooling. *International Journal of Heat & Mass Transfer, 93*, pp. 516-528. 2016.

[15] J. Wang *et al*. Ionic Wind Development in Corona Discharge for LED Cooling. *IEEE Transactions on Plasma Science, 46*(5), pp. 1821-1830, 2018

[16] M. Kilic, M. Aktas and G. Sevilgen. "Liquid Cooling Performance of the Single and Multi-Led Circuit Boards Used in Automotive Lighting Systems," *2019 4th International Conference on Smart and Sustainable Technologies (SpliTech), Split,* Croatia, Croatia, June 18-21, pp. 1-5, 2019

[17] Yang, C. Y., Liu, W. C., Yeh, C. T., and Tsai, S. N. "A novel liquid cooling system for high power LED street lamp." *29th Annual IEEE Semiconductor Thermal Measurement and Management Symposium, San Jose,* CA, United states, March, 2013, pp.151-153.

[18] W. Huang, F. Chou, J. Tsai, T. Lin and J. Chou. Optimal Design of Parameters for the Nanofluid/Ultrasonic Atomization Minimal Quantity Lubrication in a Micromilling Process. *IEEE Transactions on Industrial Informatics, 16*(8), pp. 5202-5212, 2020

[19] Zhao, X., Cai, Y., Wang, J., and Li, X. Experimental study on thermal management of led automotive headlamps using heat pipes. *Heat Transfer Research, 47*(10). 2016.

[20] Bao, Ya-Chao, et al. Experimental Study on LED Heat Dissipation Based on Enhanced Corona Wind by Graphene Decoration. *IEEE Transactions on Plasma Science, 47*(8), pp. 4121-4126. 2019.

[21] Chen, I. Y., Guo, M. Z., Yang, K. S., and Wang, C. C. Enhanced cooling for led lighting using ionic wind. *International Journal of Heat & Mass Transfer, 57*(1), pp. 285-291. 2013.

[22] Chen, I. Y., Chen, C. J., and Wang, C. C. Influence of electrode configuration on the heat transfer performance of a led heat source. *International Journal of Heat & Mass Transfer, 77*, pp. 795-801. 2014.

[23] Tamdogan, E., Arik, M., and Dogruoz, M. B. Direct liquid cooling of high flux led systems: hot spot abatement. *ASME 2013 International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems*, Burlingame, CA, United states, July 2013.

[24] Li, C., Luo, Y., Zhou, C., & Shan, Q. Charging method of micro heat pipe for high-power light-emitting diode. *Iet Micro & Nano Letters, 10*(10), pp. 518-522. 2015.

[25] Wang, N., Li, H. W., Ding, C., Shi, L. Y., Jia, H. Z., Ren, Z. D., and Zhao, Z. Y. A double-voltage-controlled effective thermal conductivity model of graphene for thermoelectric cooling. *IEEE Transactions on Electron Devices*, 65(3), pp. 1185-1191. 2018.

[26] Wang, J., Zhao, X. J., Cai, Y. X., Zhang, C., and Bao, W. W. Thermal model design and analysis of high-power led headlamp cooling device based on the thermoelectric effect. *IEEE Transactions on Components Packaging & Manufacturing Technology, 5*(5), pp. 641-649. 2015.

[27] Li, J., Zhang, X., Zhou, C., Zheng, J., Ge, D., and Zhu, W. New applications of an automated system for high-power leds. *IEEE/ASME Transactions on Mechatronics, 21*(2), pp. 1035-1042. 2016.

[28] Arik, M. An Experimental and Computational Study on Efficiency of White LED Packages with a Thermo-caloric Approach. *IEEE Transactions on Components, Packaging and Manufacturing Technology,* vol. 7(2), pp. 201-207, Feb. 2017.

[29] P. Fredes, U.Raff, E. Gramsch, J. Pascal, and J. Cuenca. Junction temperature control of UV-C LEDs based on a thermoelectric cooler device, *Microelectronics Reliability,* vol. 98, pp. 24-30, July 2019.

[30] Y. David-Shiloah, O. Raz, M. Laufer, V. Menaker, and M. Ahmad. "Auxilliary embedded coolant channels for peltier based liquid cooling solution for high power components", *2017 16th IEEE Intersociety Conference on Thermal and Thermomechanical Phenomena in Electronic Systems. Orlando*, FL, United states, May 30 - June 2, pp.774-778, 2017.

[31] X. H. Lin, S. P. Mo, L. S. Jia, Y. Zhi, Y. Chen, and Z. D. Cheng. "Experimental study and Taguchi analysis on LED cooling by thermoelectric cooler integrated with microchannel heat sink". *Applied Energy*, vol. 242, no. 15, pp. 232-238, May 2019.

[32] N. Wang, C. Gao, C. Ding, H. Z. Jia, G. R. Sui, and X. M. Gao "A Thermal Management System to Reuse Thermal Waste Released by High-Power Light-Emitting Diodes," *IEEE Trans. Electron Devices*, vol. 66, no. 11, pp. 4790-4797, Nov. 2019.

[33] L. Lin, Y. F. Zhang, H. B. Liu, J. H. Meng, W. H. Chen, and X. D. Wang. A new configuration design of thermoelectric cooler driven by thermoelectric generator. *Applied Thermal Engineering*, vol. 160, Sept, 2019.