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Self-sufficient energy recycling of light emitter diode/thermoelectric generator module for its active-cooling application

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ABSTRACT

This paper presents the energy recycling and self-sufficient application of a novel high-power light emitting diode integrating with a thermoelectric generator module. The proposed lighting module in which a thermoelectric generator device is sandwiched between light emitting diode device and heat sink autonomously recycles the waste heat to self-sufficiently support for its active cooling with an electrical fan. The start-up responses of illuminance, temperature, current and power for the proposed module were evaluated through experimental measurement. The corresponding mathematical model was derived and simulation model was built using MATLAB/Simulink for verification. The illuminance, electrical, and thermal performances have a close agreement between experiment and simulation results. The technological viability about both autonomous operation and self-sufficient energy recycling for the novel module with the active cooling was validated. Compared with passive-cooling devices, the proposed module declines the working temperature and improves illuminance simultaneously.

1. Introduction

With the advantages such as low power consumption, high efficiency, diverse colors and flexible styles, good reliability and long lifetime, light emitting diode (LED) devices have been replacing conventional lamps for the past few decades rapidly. Especially, the luminous efficacy (lumen per watt) of high-power (HP), high-brightness (HB) LED device has been progressing promisingly and its applications have been emerging dramatically into lighting market in recent years. However, the luminous flux of LED decreasing with the junction temperature leads to performance degradation. The thermal problem is consequently attracting more and more attentions. Buso et al. [1] pointed out the limiting factors of the maximum luminous output are quantum efficiency and junction thermal resistance of LED devices. As presented by Trevisanello et al. [2], the degradation rate of luminous efficacy of aged LEDs could drop up to 1%/°C with the increment of junction temperature. Therefore, a commercialized HP LED light module is commonly assembled by LED devices with a proper optical design and a heat dissipation mechanism. Generally speaking, there are two methods to remove heat. One is the passive solution that can transfer heat into ambient without additional power consumption. Either fin/pin-type heat sink or heat pipe is presently the mainstream in LED industry due to the superior characteristics in reliability and cost. The natural convection heat transfer for a radial fin-type heat is significantly enhanced up to 43% with a hollow cylinder [3]. Furthermore, Park et al. [4] proposed a chimney structure to enhance the natural convection efficiency up to 20% as compared the same radial heat sink with a hollow cylinder for the LED downlight application. An oscillating heat pipe proposed by Lin et al. [5] obviously decreased the temperature of LED device with the inclination angles of 30°/60° and horizontal/vertical operation modes. The proposed heat pipe can decrease the LED temperature about 7 °C with increasing inclination angle up to 60° or in vertical mode. Lu et al. [6] proposed a flat heat pipe to improve the heat transfer performance by considering the filling rates and inclination angles. The better thermal transfer efficiency is under the conditions of the inclination angle of 15° and the fill ratio about 30%. Faranda et al. proposed a bidirectional heat dissipation with refrigerating liquid (silicon fluid) and heat sink that improves the front heat emission [7]. Lai et al. [8] used water with some additives as a circulating liquid medium for automotive LED lighting application. Moreover, a novel air-cooling for automotive headlamp proposed by Jang and Shin [9] significantly lowers the LED temperature from 70.6 °C to 30.25 °C with circulating speed from 0 to 120 km/h and air temperature of 25 °C. Dean and Liu presented a liquid metal ($GaIn_{20}$) as the coolant for LED active cooling solution [10]. Meanwhile, some novel methods or advanced

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Nomenclature

A_{HS} (A_{LED}) area of heat sink (LED) (m^2)
C_{HS} (C_{LED}) specific heat of heat sink (LED) (kJ/(kg K))
D_{Fin} fin depth (m)
E_v illuminance of LED (lux)
G_{E2L} (G_{E2T}, G_{T2L}) transfer function relating electric to luminous (electric to temperature, temperature to luminous) (lux/W, °C/W, lux/°C)
H height (m)
h_{Conv} (h_{Fin}) (fin) convection coefficient (W/(m^2 K))
I output current of TEG in ampere (A)
L length (m)
m_{HS} (m_{LED}) mass of heat sink (LED) in kilogram (kg)
P_{LED} input power of LED device in watt (W)
Q_{AF} heat transfer extracted by airflow in watt (W)
Q_{HS2Amb} heat loss from heat sink to ambient in watt (W)
Q_J Joule heat loss for TEG in watt (W)
$Q_{LED2Amb}$ (Q_{LED2HS}) heat transfer from LED to ambient (heat sink) in watt (W)
Q_{PA}/(Q_{PE}) absorbed/emitted Peltier heat of TEG in watt (W)
Q_{TH} heat transfer of thermal conduction for TEG in watt (W)
R_{TEG} TEG resistance (Ω)
S_{TEG} Seebeck coefficient of TEG
T_{AF} (T_{Amb}, T_{Out}) airflow (ambient air, outlet airflow) temperature in Kelvin (K)
T_{HS} (T_{LED}) heat sink (LED junction) temperature in Kelvin (K)
U_S Seebeck voltage of TEG in voltage (V)
V output voltage of TEG in voltage (V)
v_{AF} (v_{Air}) airflow (air) speed (m/s)
W (W_{Fin}) (fin) width (m)

Greek letters
λ_{LED} heat dissipation coefficient of LED
η_{Fin} fin efficiency
κ_{Fin} (κ_{TEG}) thermal conductivity of fin (TEG)

Subscripts
AF airflow
Air air
Amb ambient
Conv convective
E2L (E2T, T2L) electrical–luminous (electrical–thermal, thermal–luminous)
Fin fin
HS heat sink
J Joule heat
LED light-emitting diode
Out outlet
TEG thermoelectric generator
TH heat transfer of thermal conduction

technologies, such as microjet array cooling, microgap channel cooling, thermoelectric cooler, and piezoelectric fan were studied. Luo and Liu [11] showed the temperature of a LED device with rated power of 227 W is about 69.4 °C using a microjet cooling system at the room temperature of 30.8 °C. The optimization of microjet structure was further studied by the simulation of computational fluid dynamics [12]. Kim et al. proposed the microgap cooler with a dielectric FC-72 fluid that was directly mounted on a LED package [13]. Thermoelectric cooler system for LED devices was studied and has better cooling ability [14,15]. However, a LED array with a rated power of 18 W consumed 2.9 W for decreasing the LED temperature of 7 °C [14]. Sufian et al. [16] proposed a piezoelectric fan method for a high power LED array, which drastically reduced the LED temperature from 109 °C to 60 °C. The leakage and evaporation of liquid coolant are the main problems for LED heat dissipation in practice. Additional energy consumption is another issue for these active cooling methods. So far, the waste heat recovery of LED devices using thermoelectric generator (TEG) for LED's own active cooling methods is not proposed yet. The summary for reviewing the cooling technologies of LED devices is listed in Table 1. This paper reveals not only a summary review for the heat dissipation technologies of LED device but presents a method for the air-cooling of novel TEG/LED module operating with self-sufficient function, in which the TEG device recovers LED's waste heat and converts into electricity for power consumption of an electrical fan. The incentives using TEG for LED lighting are (1) to autonomously recover the waste heat of LED devices and self-sufficiently drive an electrical fan for its own active cooling without additional assistance, (2) to simultaneously improve energy efficiency and luminous efficacy in a recycling process, and (3) to take all the reliability, system complexity, and cost-effectiveness into consideration.

Furthermore, the corresponding model for the novel LED/TEG module is proposed to predict the system behaviors and validate the experimental findings in a cost-effective way. In order to have a good quality in lighting control, optical performance, and reliability of LED device, Huang et al. developed the dynamic model of HP LED lighting system by the system identification [17] and system dynamics [18], respectively. A steady-state photo-electro-thermal (PET) theory was developed to correlate the photometric, electrical, and thermal characteristics of LED system [19]. Tao and Ron Hui [20] further developed a dynamic PET model by considering their time-domain dynamics. On the other hand, the TEG model implemented by Simulink has been developed [21]. Up till now, no detailed model for TEG-driven air cooling of HP LED is reported in literatures. The mathematical model for the integrated LED/TEG module and heat sink with an electric fan for active cooling is derived. The simulation model is built using MATLAB/Simulink software. The time-domain responses are studied through measurement and simulation in the meantime. The self-sufficient function of the proposed active-cooling LED/TEG system is demonstrated and evaluated.

2. Novel LED/TEG module

2.1. LED/TEG with active cooling configuration

The utility model patent of the novel LED/TEG module collector was issued on January 13, 2013 in Taiwan [22]. An integrated LED/TEG module with a fin-type heat sink and an electrical fan was implemented in this paper. The schematic diagram is depicted in Fig. 1. As shown in Fig. 1a, the TEG module, sandwiched between LED module and heat sink, is used to extract the waste heat from LED device and generate DC electricity to supply power for the fan operation. A fin-type heat sink is assembled as an air cooler in which the fins with a large ratio of depth to separated width are attached at the cool side of TEG module. An electric fan is driven by the TEG module through a DC–DC booster converter and provides force-convection airflow through the fin surface of heat sink to enhance the heat dissipation.