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An experimental study on the heat dissipation of LED lighting module using metal/carbon foam[☆]

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ABSTRACT

In this study, thermal performance of the cooling modules applicable for Par 38 light bulb is investigated. A total of six heat sink modules, including the basic reference design, metal foam, and carbon foam are tested and compared. Tests are performed and analyzed using the transient test method based on JESD51-1 standard. It is found that the thermal resistance from junction to die attach is quite small. By contrast, the thermal resistance of the heat sink dominates the total resistance, and it comprises 55% of the total resistance for the standard heat sink module. With some slight opening on the base plate, the thermal resistance can be improved by approximately 12%. The thermal resistance for the carbon foam having an embedded metal plate shows the least thermal resistance of 1.14 K/W, followed by the carbon foam, and then the metal foam. The lower thermal resistance of carbon foam in association with copper metal foam is due to its higher emissivity. In addition to better heat transfer performance as compared to the standard plate heat sink, the utilization of carbon foam and metal foam can also significantly reduce the weight of the heat sink. In this study, the weight of the heat sink can be reduced as much as 33%.

1. Introduction

The light-emitting diode (LED) is a semiconductor light source emitting light operated at a specific wavelength. Note that when compared to fluorescent and incandescent lighting, LEDs feature fast response time, simple structure, environmental benign, vivid colors, high energy efficiency, longevity, and easier to put into mass production. Hence, LEDs are gradually replacing traditional light sources in every aspect of lighting applications because of their versatile benefits. However, in practice LED converts only 15–30% power input into light, leaving 70–85% energy into heat. In this regard, effective thermal management of the LED lighting is imperative to avoid failure of the LEDs [1].

Thermal managements of LED lighting span three major categories: the package level, the board level, and the system level [2]. Thermal management in package level or board level involves the selection of die structure [3], die bonding material [4,5], and substrate [6]. In practice, the thermal resistance of the system level is very crucial. This is because the size of heat sink implemented at system level normally takes up the majority of the space, weight, and surface area of the lamps and lanterns. In fact, the weight of the heat sink used in LED lighting can easily surpass 70% of its total weight. In this regard, it is crucial to reduce the size and weight of the heat sink from the standpoint of practical applications. As a consequence, cellular structure like metal foam or carbon foam can be considered as the heat sink applicable for LED lighting due to its significant reduction of weight while still retains a gigantic specific surface area for heat dissipation. There had been numerous studies associated with metal foam concerning influences like of PPI [7], and porosity [8,9] on the overall performance. Experimental and numerical studies for metal foam were also reported [10–12]. The prior study by Hsieh and Wu [13] indicated that the Nusselt number of metal foam is increased with PPI. This is because more air flow can penetrate into the internal porous structure and promote convective heat transfer. However, the rise of PPI also leads to a decline of thermal conductivity and may even deteriorate heat transfer [14].

In summary of the foregoing studies, cellar structures are considered to be very effective in heat transfer augmentation and weight reduction in natural convective applications. Hence, it is the objective of this study to investigate its applicability in typical LED applications as compared to the standard plate fin heat sink design. The cellar structures include copper metal foam and carbon foam.

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Nomenclature

C [W s K^{-1}]	Thermal capacitance
I_F [A]	Forward current
I_H [A]	Heating current
I_M [A]	Measuring current
K [W^2 s K^{-2}]	Differential structure function
K_f [K/V]	K factor
k [W m^{-1} K^{-1}]	Thermal conductivity
t_f [mm]	Thickness of copper plate fin
t_{foam} [mm]	Thickness of copper or carbon foam
$W_{opening}$ [mm]	Width of opening
R [K/W]	Thermal resistance
T_j [°C]	Junction temperature

Greek symbols

ΔT_j	The change in the LED's junction temperature
V_f [V]	The change in the LED's forward voltage

Subscripts

amb	Ambient
Chip	LED chip
DA	Die attach
HS	Heat sink
MCPCB	Metal Core Printed Circuit Board
th	Thermal
TP	Thermal pad
sub	substrate

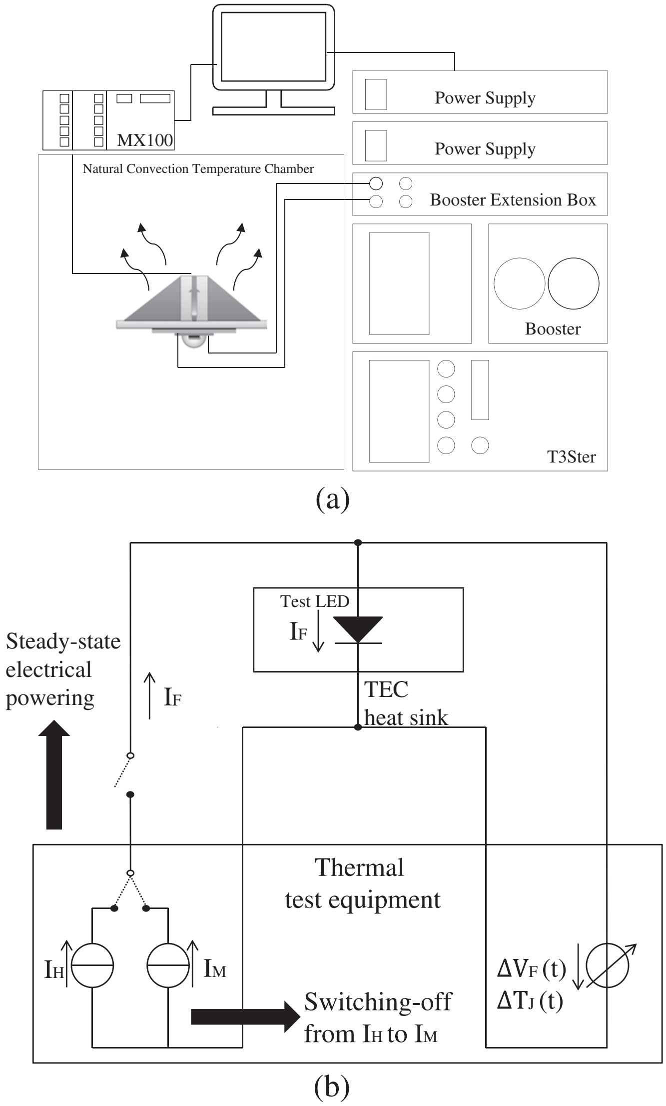

Fig. 1. Schematic of the (a) test setup (b) conceptual connection circuit for thermal circuit.

2. Experimental setup and data reduction

The schematic of the test facility is shown in Fig. 1(a) which contains an environmental chamber, a data acquisition system, a transient test measuring system (T3ster measuring system), a booster extension box, a power supply, and the test LED lighting module. The concept thermal circuit of the measurement system is depicted in Fig. 1(b). The high voltage LED lighting module is typically 1400 lm. The environmental chamber can regulate and control the ambient temperature. The ambient temperature is controlled at 25 ± 0.3 °C throughout the experiments. A total of six heat sinks are used for testing and comparing in a LED module as shown in Table 1. Detailed geometrical configurations can be seen in Fig. 2. The thickness of the base plate is 2 mm while a total of six fins having triangular configuration were mounted on the base heat sink module. The test sample #1 is the reference heat sink with a solid copper fin. Test sample #2 is identical to sample #1 except that there are some openings on the base plate. The opening is used to entrain more air from the base plate to augment heat transfer. Test sample #3 is similar to sample #1 but it replaces the copper fin with the metal foam. For sample #4, the metal foam is brazed on the copper plate. Samples #5 and #6 are similar to those of samples #3 and #4, but the metal foam is replaced by carbon foam. Both copper foam and carbon foam feature a relatively uniform distribution of pore sizes and open cell structure; the copper foam is taken from the commercially available samples and the carbon foam is made by us.

The homemade carbon foam derived from a pitch precursor because pitch is the only precursor which forms a highly aligned graphitic structure which is normally a requirement for high conductivity. The pitch was melted in 140 to 450 °C range and has risen to 400–500 °C range, causing the low molecular weight compounds in the pitch to vaporize, resulting in a pitch foam. Then, the pitch foam must be oxidatively stabilized by heated air. In this regard, the structure must be cross-linked and the pitch must be set so it does not melt during carbonization. The set or oxidized pitch is then carbonized in an inert atmosphere to temperatures as high as 1100 °C. Then, graphitization is performed at temperatures as high as 3000 °C to produce a high thermal conductivity graphitic structure. The thermal conductivity of a highly aligned graphitic structure in the struts was estimated to be 1700 W m^{-1} K^{-1}. Carbon foam is a highly porosity material with k being about 150 W m^{-1} K^{-1}, and its density is only one-fifth of the aluminum. The surface area is roughly 100 times that of the traditional heat exchanger.

The power supply into the LED module is about 9.5 W with the operational voltage and current of 267 V and 0.036 A, respectively. To minimize the thermal contact resistance, a thermal pad with $k = 2.8$ W m^{-1} K^{-1} is used amid the LED and thermal module.

The thermal resistances of the test samples are measured using the transient test method based on EIA/JESD51-1 standard [15] (Electrical Test Method) and a transient dual interface measurement (TDIM) based on the JESD51-14standard [16]. A T3Ster Master system was used to measure the total thermal resistance of a LED based on thermal