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Innovative analytic and experimental methods for thermal management of SMD-type LED chips

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ABSTRACT

In this study, we propose innovative analytic and experimental methods for thermal management of SMD-type LED chips: a geometry optimization algorithm of natural convective heat sinks together with a novel technique for estimation of the LED surface temperature. An analytic algorithm for the optimal design of the LED heat sink is proposed. By using this algorithm, the optimal fin configuration and corresponding thermal performance of the heat sink can be readily predicted according to the inputted base plate dimensions, ambient condition, heat dissipation rate, and LED chip distributions. In addition, a novel experimental technique for an accurate measurement of the LED junction temperature is proposed based on infrared thermometry and an isothermal chamber with an observation hole. The LED junction temperature is also measured using T3ster method, and the results are compared with those from the aforementioned infrared thermometry and analytic procedure. The proposed analytic and experimental results are shown to agree with each other well. The present analytic model is well validated by experimental results, and can be widely utilized for designing the cooling system related to various LED products.

1. Introduction

Effective cooling technology is regarded as an important requirement for a reliable operation of electronics devices [1,2]. The heat sinks are well known, and the most widely employed cooling module for concurrent electronic industries [3,4]. The heat sinks are generally classified as natural convective heat sinks and the forced convective heat sinks, in accordance with the heat flux of the considered applications [5,6]. Compared with forced convective heat sinks that accompany the fan system, natural convective heat sinks have various advantages such as simple structure long-term reliability [7,8]. In this regard, the natural convective heat sinks are widely used in many other applications in addition to electronics, such as home appliances, telecommunication units, and LED devices [9,10]. Particularly, the heat sinks in LED devices should be fanless, and thus, subject to natural convection, in order to ensure the long lifetime and high competitiveness of the product. The LED heat sinks generally have radial configuration [11] to meet the geometric constraint of the lighting devices. However, some LED devices, such as headlight or daytime running light of vehicles, associate conventional plate fin heat sinks, whereas the heat sink is positioned inside the lighting module of the vehicle. These kinds of heat sink face a strong limitation on its dimension, as well as very high ambient temperature typically amounts to 100 °C. This may result in a significant change in flow and heat transfer characteristics compared with conventional natural convective heat sinks, and thus, existing design guidelines for natural convective heat sink cannot be valid.

Another problem lies within the fact that the LED chips are very highly localized heat sources in thermal perspective of view, whose lateral dimension is typically $O(1\ \mathrm{mm})$. For the substrates with localized heat sources, the spreading thermal resistance can constitute a significant portion in overall thermal resistance. The spreading thermal resistance refers to the thermal resistance which occurs when the heat flows out of narrow region into wider region [12]. In such a heat sink where the effect of spreading thermal resistance is significant, the thickness of the base plate should be carefully designed. However, conventional design methods for natural convective heat sinks have been generally focused on only the fin spacing and the fin height. In the aforementioned LED devices, the spreading thermal resistance not only takes place in the heat sink base plate, but also in the PCB where the LED chips are mounted. Therefore, the spreading thermal resistance should be

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Nomenclature

A	Area [m^2]
El	Elenbaas number [m^2]
g	gravitational constant [m/s^2]
h	heat transfer coefficient [W/m^2 K]
H	height [m]
H_b	substrate thickness [m]
H_f	fin height [m]
H_{tot}	total heat sink height [m]
k	thermal conductivity [W/mK]
L	heat sink length [m]
n	number [–]
Nu	Nusselt number [–]
Pr	Prandtl number [–]
Q	heat transfer [W]
q	heat flux [W/m^2]
R	thermal resistance [K/W]
Ra	Rayleigh number [–]
s	fin spacing [m]
T	temperature [K]
t	fin thickness [m]
W	heat sink width [m]
x,y,z	coordinates [m]

Greek symbols

α	thermal diffusivity [m^2/s]
β	thermal expansion coefficient [1/K]
ε	heat source size normalized by the heat sink size [–]
ε_{eff}	effective emissivity [–]
η	fin efficiency [–]
θ	temperature difference [K]
ν	kinematic diffusivity [m^2/s]
σ	Stephen-Boltzmann's constant

Subscripts

∞	ambient [–]
b	base, or substrate [–]
eff	effective [–]
f	fluid or fin [–]
fin	fin [–]
HS	heat sink [–]
rad	radiation [–]
tot	total [–]

doubly considered in addition to the natural convection thermal resistance, in determining the overall thermal resistance. In addition, the thermal contact resistance at the TIM (thermal interface material) between the PCB and the heat sink should also be taken into account in the proposed design method.

In order to validate the proposed design method, experimental results for the thermal performance of the LED system should be presented. In regard to the experiment, there is another problem in the concurrent studies in that it is impossible to directly measure the junction temperature of the LED, because the LED is not exposed, but covered with encapsulent and lens. In this regard, the junction temperature of the LED has been predicted indirectly by measuring the temperature at the electrode [13] or by measuring electrical impedance using T3ster facility [14], which can result in inaccurate prediction on the junction temperature. Therefore, a new technique for measuring the LED junction temperature is required, together with the aforementioned new design method.

In this study, we propose innovative analytic and experimental methods for thermal management of SMD-type LED chips: a geometry optimization algorithm of natural convective heat sinks together with a novel technique for estimation of the LED surface temperature. An analytic algorithm for the optimal design of the LED heat sink is proposed. By using this algorithm, the optimal fin configuration and corresponding thermal performance of the heat sink can be readily predicted according to the inputted base plate dimensions, ambient condition, heat dissipation rate, TIM properties and LED chip distributions. In addition, a novel experimental technique for an accurate measurement of the LED junction temperature is proposed based on infrared thermometry. The present analytic model is well validated by experimental results, and can be widely utilized for designing the cooling system related to various LED products.

2. Analytic design method

2.1. Heat sink consideration

The problem in this study considers a natural convective flow through a vertically-oriented plate fin heat sink as depicted in Fig. 1. The heat sink length (L), width (W), total heat dissipation (Q_{tot}) are given as the input parameters, and the fin height (H_f) is the swept parameter. The fin thickness is dependent on the fin height when the heat sink is die-casted. In this study, the correlation between H_f and t is set as follows:

$$t_{base} = t_{tip} + 2H_f \tan\alpha \quad (1)$$

$$t = \frac{t_{tip} + t_{base}}{2} \quad (2)$$

where t_{tip} is the fin tip thickness, α is the draft angle of the die-casted fin, and t_{base} is the fin thickness at the base. The total heat transfer rate through the heat sink is given as the sum of the heat transfer at the fin surfaces, the heat transfer at the exposed surface of the base plate, and the radiation heat transfer, as follows:

$$Q_{HS} = n_{fin}Q_{fin} + h_b A_b \theta_b + Q_{rad} \quad (3)$$

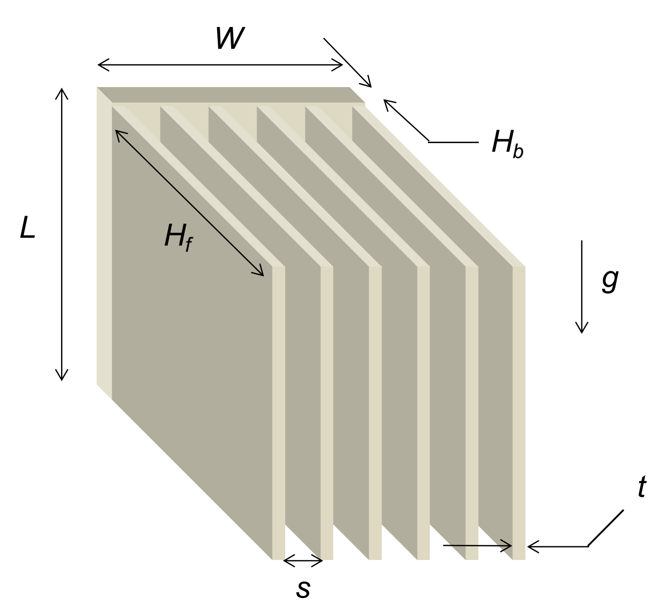

Fig. 1. Schematic diagram of heat sink considered in this study.