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Simulation and evaluation of the peak temperature in LED light bulb heatsink

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ABSTRACT

Heat dissipation in LED light bulb has been one of the key factors in affecting the efficiency and lifetime of the LED. The commercially available high-power LED light bulbs often come with a bulky heatsink to keep the temperature of the light bulb in a reasonable range. Unfortunately, the heatsink designs of most of the commercial products are not optimized in terms of cooling efficiency, dimension, and material cost. Indeed, optimization of the heatsink design is a time-consuming and sophisticated process. It requires a powerful computational fluid dynamics tool to perform computer simulation. With the aid of computer simulation based on a simple heat conduction model together with some measurement results, this work presents a rapid evaluating tool for predicting the peak temperature of a heatsink by using the concept of effective heat conductivity. It provides a simple way to predict the peak temperature change for different designs.

1. Introduction

Light-emitting diode (LED) has been recognized as the ultimate light source because it's high energy efficient, compact and extremely long life [1–3]. The replacement of conventional lighting systems with LED light sources has been accelerated recently and that a number of reliability issues come across to the customers. The reported lifetime for a LED can exceed 35 thousand hours, but it is often observed that the commercial LED light bulbs experience significant light intensity degradation and even an early failure after a couple thousand hours operation [3,4]. According to a comprehensive study on a number of commercially available LED lamps conducted by the Hong Kong Consumer Council, all the LED lamps under-test experienced 7.1 to 28.2% light intensity drop after 3000 h of operation. One sample even experienced an early failure after 2800 h operation [4]. Yet the degradation and failure are due to many different regimes. It can be due to the metal migration or wear-out of the metal contacts and solders [5–7]; it can be due to the yellowing of phosphor reflector [8–10]; and it can also be due to the defect generation in the device active region [7,11,12]. The light intensity degradation, and in some cases the early failure, are mostly related to the temperature effects. It has been found that a LED operated at a high operation temperature (e.g. >70 °C) can lead to a notable red shift of light spectrum, significant light intensity reduction, and lifetime shortening [12]. Temperature is an acceleration factor for most of the failure and degradation mechanisms as mentioned [9,10,12]. Hence, heatsink design is of vital importance for maintaining the performance and endurance of the LED lamps [13–15]. In fact, most of the heatsink designs in the available LED products were not optimized and yet simply based on the “total surface area” rule of 64 cm^2/W which are not the best design in terms of cooling efficiency, shape, dimension, and material cost in most cases. In addition, most of these heatsinks were in radial form and were designed for best convection in vertical placement [15–17]. This assumption is not valid in many cases. In real applications, the LED lamp can be placed with a certain tilt angle, horizontal, up-side down, in a semi-closed or completely closed chamber, convection could be quite inefficient in these cases.

Fig. 1 shows the temperature profiles for a commercial 9.5 LED lamp with a bulky aluminum heatsink. The diameter and length of this heatsink are 5.5 cm and 4.5 cm, respectively; and there are 26 vertical fins in total to enhance the convective heat transfer. As shown in Fig. 1, although the temperature distributions look similar, the peak temperatures are quite different when the LED lamps are placed in different orientations. As the fins are aligned in the vertical direction, heat reduction should be most effective when the lamp is placed vertically although the heat distributions for vertical up and vertical down placements are still quite different. Nevertheless, the peak temperature for vertical placement still exceeds 60 °C indicating it is not a good design. It is even worst when it is placed horizontally, the peak temperature increases up to 71 °C. Long-term operation of LED at that temperature will shorten its lifetime significantly [12]. Hence, it is not difficult to imagine how important of the heatsink design will be for higher power lighting applications. However, the optimal heatsink design is a formidable task as there are too many factors needed to be considered in particular with the presence of airflow convection [18]. The usual

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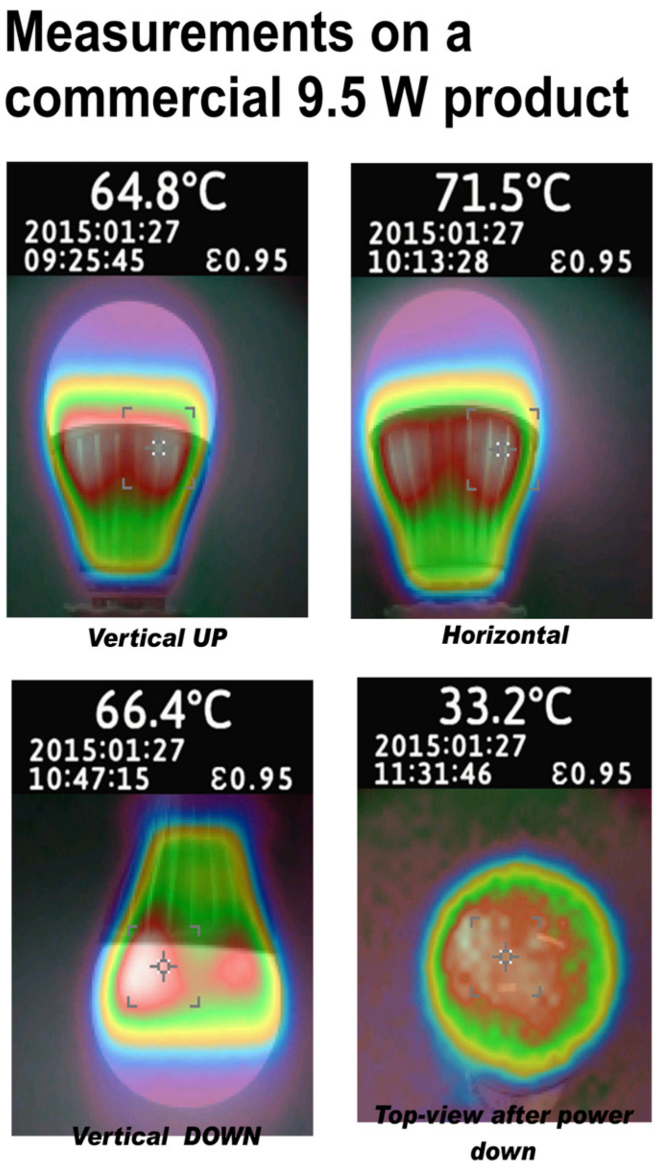

Fig. 1. Typical heat distribution of LED lamp placing at different orientations as revealed by visual IR thermometer measurement.

approach is the use of computational fluid dynamic simulation tool which is quite time consuming [13–21]. The objective of the present work is to build a simplified mathematical model and to develop a rapid heatsink evaluation method by using some mathematical techniques such as the use of implicit finite difference method (IFDM) for evaluating the heat conduction equation in the spherical coordinate system for the core part of LED heatsink. The effect of convection in the peak temperature will be dealt with the concept of effective conductivity derived from simulation and experimental measurements.

2. Numerical calculation

To obtain the temperature distribution of the heatsink so as to perform better modeling and proper approximation and to provide an intuitive picture on the heatsink design, we calculate the temperature distribution from first principle based on the heat conduction equation [21,22]. Finite difference method in the polar form with cylindrical symmetry was used to reduce the calculation time. Fig. 2 shows the schematic of the heatsink structure and coordinate used in this simulation. The heat conduction is described by Eq. (1). Note that here no convection and radiation heat transfer is considered at the present stage in order to make the calculation simple and to have clear picture on the intrinsic aspect of heat conduction. Convection effect will be approximated by the concept of effective thermal conductivity of the heatsink material with specific surface area which will be discussed in Section 3.

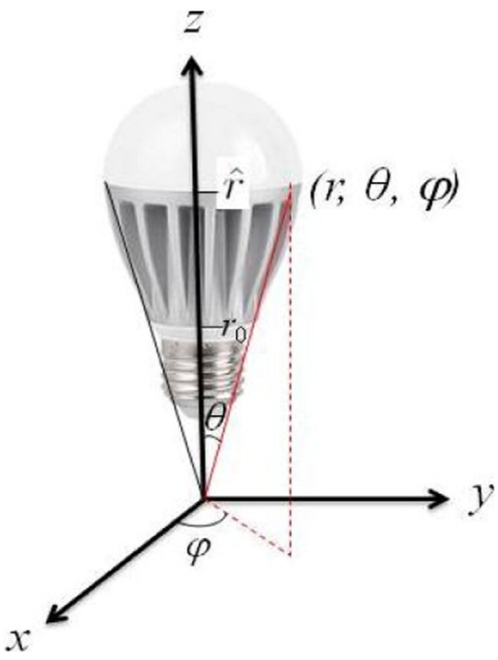

Fig. 2. Coordinate system used for developing the heat conduction program for LED light bulb heatsink.

In general, considering an isotropic homogenous material, the heat transfer equation in the polar form can be expressed as [21]:

$$\frac{\partial U}{\partial t} = \alpha\left(\frac{\partial^2 U}{\partial r^2} + \frac{1}{r^2}\frac{\partial^2 U}{\partial \theta^2} + \frac{1}{r^2 \sin^2\theta}\frac{\partial^2 U}{\partial \varphi^2} + \frac{2}{r}\frac{\partial U}{\partial r} + \frac{1}{r^2 \tan\theta}\frac{\partial U}{\partial \theta}\right) + \frac{q_v}{\rho c}\exp\left(-a\left(r^2 - 2\hat{r}r\cos\theta + \hat{r}^2\right)\right) \tag{1}$$

where U is temperature, q_{v} the generated heat, c the specific heat capacity, ρ the density of heatsink material; α is the thermal diffusivity which is given by $\kappa/\rho c$, here κ denotes the thermal conductivity of the heatsink material. Note that the last term in Eq. (1) is an approximation of the point heat source. This treatment enables the finite difference discrtization on the heat source also. By changing the material parameters at different regions, inhomogenous material can be done with the same equation. The boundary conditions are given as following:

(i) When $r = \hat{r}_0$ or $r = \hat{r}, 0 \le \theta < \hat{\theta}_1, 0 \le \varphi \le 2\pi; \hat{\theta}_1 \le \theta \le \hat{\theta}_2, (2i-2)\frac{2\pi}{N} \le \varphi \le (2i-1)\frac{2\pi}{N}, i = 1, 2, \ldots, \frac{N}{2}, \alpha = \alpha_2, \kappa = \kappa_2, \rho = \rho_2, c = c_2$

(ii) When $\hat{r}_0 < r < \hat{r}, 0 \le \theta \le \hat{\theta}_0 (\hat{\theta}_0 < \hat{\theta}_1), 0 \le \varphi \le 2\pi, \alpha = \alpha_1, \kappa = \kappa_1, \rho = \rho_1, c = c_1$

(iii) When $\hat{r}_0 < r < \hat{r}, \hat{\theta}_0 < \theta < \hat{\theta}_1,\ 0 \le \varphi \le 2\pi;\ \hat{\theta}_1 \le \theta \le \hat{\theta}_2,\ (2i-2)\frac{2\pi}{N} \le \phi \le (2i-1)\frac{2\pi}{N}, i = 1, 2, \ldots, \frac{N}{2}, \alpha = \alpha_2, \kappa = \kappa_2, \rho = \rho_2, c = c_2$

(iv) When $t = 0,\ \hat{r}_0 \le r \le \hat{r},\ 0 \le \theta < \hat{\theta}_1,\ 0 \le \varphi \le 2\pi;$ or $\hat{\theta}_1 \le \theta \le \hat{\theta}_2, (2i-2)\frac{2\pi}{N} \le \phi \le (2i-1)\frac{2\pi}{N},$

$$U(r, \theta, \phi) = U_{amb}$$

where U_{amb} is the room or ambient temperature which is assumed to be a constant.

(v) When $r = \hat{r}_0,\ 0 \le \theta < \hat{\theta}_1,\ 0 \le \varphi \le 2\pi;$ or $\hat{\theta}_1 \le \theta \le \hat{\theta}_2,\ (2i-2)\frac{2\pi}{N} \le \varphi \le (2i-1)\frac{2\pi}{N},$

$$-\kappa_2 \frac{\partial U}{\partial r}\Big|_{r=\hat{r}_0} = H_1\left[U_{amb} - U\big|_{r=\hat{r}_0}\right]$$