Applied Thermal Engineering 95 (2016) 482–490

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

A hybrid prediction method on luminous flux maintenance of high-power LED lamps

Miao Cai [a], Daoguo Yang [a,*], Kunmiao Tian [a], Wenbin Chen [a], Xianping Chen [a], Ping Zhang [a], Xuejun Fan [b], Guoqi Zhang [c]

[a] School of Mechanical and Electrical Engineering, Guilin University of Electronic Technology, Guilin, 541004, China
[b] Department of Mechanical Engineering, Lamar University, Beaumont, Texas 77710, USA
[c] Delft Institute of Microsystems and Nanoelectronics (Dimes), Delft University of Technology, Mekelweg 6, 2628CD Delft, The Netherlands

HIGHLIGHTS

- Thermal modeling and temperature measuring are applied to predict the T_j of LED lamps.
- The lumen maintenance of LED lamps is further estimated with the predicted T_j.
- The thermal resistance model of LED lamps is simplified into a one-dimensional model.
- The estimation method is efficient to predict the luminous maintenance of LED lamps.
- The proposed method is expected to be useful for the fast qualification of LED lamps.

ARTICLE INFO

Article history:
Received 23 June 2015
Accepted 10 November 2015
Available online 1 December 2015

Keywords:
High-power LED lamp
Luminous flux maintenance
Lifetime prediction
Thermal modeling
Junction temperature
Thermal measurement

ABSTRACT

A hybrid method, applied thermal modeling and temperature measurement, is proposed to estimate the junction temperature (T_j) of high-power light-emitting diodes (*LEDs*) at system level, and further project long term lumen maintenance of *LED* lamps. First, 3D finite element modeling on commercial *LED* lamps is performed based on lamp structure and material information to find a steady and reliable relationship between the junction point and a referenced point on the heat sink. Then, accurate thermal measurement is conducted on the heat sink to calibrate and verify the finite element model. The predicted T_j of *LEDs* from modeling, in conjunction with *LM-80* luminous maintenance data using *TM-21*, is applied to project the luminous flux depreciation at the system level. The proposed approach is validated by aging tests at room ambience. Results show the thermal resistance modeling can be simplified into a one-dimensional model when a *LED* lamp operates in a steady situation. Thus, the T_j of *LED* lamps operating at any specified ambient temperature can be achieved quickly. The estimation method for predicting luminous maintenance of *LED* lamps is efficient and fast. The proposed method is expected to be useful for the fast qualification of *LED* lamps.

1. Introduction

Light-emitting diodes (*LEDs*) have attracted growing attention for their advantages over traditional light sources, such as high luminous efficiency, energy saving, and long lifetime [1]. However, more than 70% of the input electrical energy is converted into heat in general commercial products [2]. With continuously increasing power density, heat generation in the active layers of *LEDs* has overheated p–n junctions. The temperature of the p–n junction, named as junction temperature (T_j), is regarded as one of crucial parameters for *LED* reliability. *LED* products suffer many problems because of high T_j, like quantum efficiency reduction, spectral shift, and color shift or even the early decommissioning of *LEDs* [3]. The reliability of *LED* products has recently become a big concern.

The lifetime of a *LED* lamp is defined by the Illuminating Engineering Society (*IES*) under their standards, *LM-79* and *LM-80*. Likewise, the Energy Star *TM-21* procedure specifies the process for lumen maintenance over time with its current input and working condition [4]. These procedures are time-consuming; for example, *LM-80* requires at least 6000 hours of testing achieving reliable long term predictions. Reports state that *IES LM-84* and *TM-28* require a minimum of 3000 hours of testing [5], and such a test duration seems still too long for the rapid development of *LED* products. In recent years, a few studies have been carried out on *LED* lamp reliability. Ignacio et al. [6] presented a reliability testing method for *LEDs* based on the overstress life test method. However, when they

* Corresponding author. Tel.: +86 07732232253; fax: +86 07732290108.
E-mail address: daoguo_yang@163.com (D. Yang).

http://dx.doi.org/10.1016/j.applthermaleng.2015.11.034
1359-4311/

tried to evaluate the reliability of portable lamps, very few lamps passed the test [6]. Considering the degradation of the epoxy lens and plastic package, Koh et al. [7] introduced simplified Eyring models to predict the life of a lighting system under changing conditions. Moreover, researchers have developed some reliability models for extrapolating the lifetime of *LED* lamp system, such as a generic system level approach [8], an approach using design for reliability [9], a hierarchical life-prediction model [10], and a nonlinear filter-based approach [11]. However, most of those methods ignore the existing reliability data from the qualification process of the *LED* package or module, and the long-term luminous depreciation testing or/and the complex reliability modeling cannot be avoided to implement those methods. Evidently, a fast lifetime prediction of *LED* lamps or luminaires remains a challenging task.

Modeling and simulation are important activities, because they can help provide an accurate prediction of final device performance and reliability [12]. Li et al. [13] launched the research to *LED* integrated light source thermal issues on the principle of heat transfer, and proved that *LED* thermal field analysis based on Multiphysics finite element simulation is accurate, feasible, and effective. Meanwhile, Ye et al. [14] developed an electrical–thermal–luminous–chromatic model to predict the light performance with thermal management under in-situ temperature while considering a series of thermal problems resulting from the drive of increased electrical currents to achieve high luminous output for phosphor-converted white *LED*. Aiming to enhance heat dissipation and further minimize T_j, many studies were conducted to fulfill thermal designs with the help of thermal modeling and analysis [15–17].

Focusing on the thermal modeling of the *LED* lamp system, Costa and Lopes [18] presented a numerical study concerning an improved heat sink for *LED* lamps operating under natural convection conditions. Further thermal module designs and analyses on 230 *W* *LED* lamps with different incline angles were carried out [19]. Meanwhile, Zhao et al. [20] conducted a thermal model design and analysis for high-power *LED* automotive headlight cooling devices, and Wang et al. [21] had a thermal design for a *LED* lamp with air convection. Modeling analysis on the thermal performance of a *LED* lamp showed that critical parts can be determined with thermal simulation tools when designing higher power *LED* lamps, and solutions for thermal problems can be achieved [21–23]. Impressively, employing a two-resistor compact thermal model, Yurtseven et al. [24] analyzed the temperature distribution of *LED* luminaires, and believed that use of the two-resistor model and measurement combination is a fast and easy way of predicting thermal behavior of the *LED* system with acceptable errors. Muller et al. [25] had further tried to address several issues regarding the determination of the junction-to-case thermal resistance for *LED* packages. Especially, the so called “point of separation” of the underlying dual-interface method was investigated; and experiments and simulations, investigating the environmental influences on this crucial point, revealed that the point of separation changes depending on the thermal boundary condition in the case of the *LED* module [25]. Evidently, thermal modeling can be employed to analyze *LED* T_j, while an effective and fast method to obtain the T_j of *LED* lamp systems has still not been achieved.

Generally, *LED* T_j measurement methods can be divided into thermal, optical, and electrical measuring methods as per a concrete measured parameter, such as measuring directly with an embedded microsensor along *LED* chip [26], determining through a stable linear relationship between T_j and *LED* light power [27,28], and a certain T_j relationship to peak wavelength or blue–white ratio of *LED* devices with self-excited photoluminescence signal [29], or to reverse current in *InGaN LEDs* [30]. Among the T_j measurement methods, the pulsed T_j measurement (*PJTM*) is the most appealing method [31–33]. The *PJTM* method is based on an evident linear relationship between *LED* T_j and its associated voltage in a certain range of temperature and the forward current. Uncertainty studies or error comparisons on T_j measurement have recently become a popular topic of discussion [34,35]. Ye et al. [36] proposed an improved pulse-free direct T_j measurement method for *HV LEDs* to reduce errors and to achieve in situ T_j measurements with *DC* currents, simpler setups, and a fewer step sequence. However, generally, *LED* packages or *LED* modules are assembled with a heat sink and an optical structure. Implementing the above T_j measurement approaches for *LED* lamps system with complex geometry structure is impractical [37], unless the system is disassembled.

Over the last decade, although many studies were carried out for *LED* packages and modules, the measurement or prediction of the lifetime of *LED* lamps or luminaires is still a big challenge. According to our previous investigation [37], the significant temperature gap of 5 °C–12 °C was found at the heat sink surface of five types of *LED* lamps with/without lampshade. This indicates that the operating ambient condition of the *LED* package or module assembled in a lamp, compared with that of the *LED* package or module alone, is more abominable, and indeed the junction temperature of the *LED* package or module assembled in a lamp is at a higher stress level. Therefore, the thermal performance of a *LED* package or module is different from a *LED* package or module assembled in a lamp. It should be highlighted that the long lifetime of a *LED* light source (or package and module) cannot translate into the long lifetime of a product if the thermal design of a *LED* product is not done properly, and the luminous maintenance test of product level is impractical. Developing a fast methodology to accurately predict the lifetime at product level is urgently needed.

In this work, a hybrid method that combines thermal modeling and temperature measurement is proposed to estimate the T_j of *LEDs* at the system level, and further to project long term lumen maintenance of *LED* lamps. Such a method will avoid the time-consuming luminous depreciation test or/and the complex reliability modeling at product level as well as overcome the measurement of soldering temperature that requires the disassembling of the system. The hybrid method is an effective and fast method for predicting the lifetime of *LED* lamps at product level with the existing reliability data of the *LED* package or module. The main ideas of the proposed method are as follows. *3D* finite element modeling is performed based on the luminaire structure and material information. Then, accurate thermal measurement is conducted on the heat sink temperature to calibrate and verify the finite element model. Predicted T_j of *LEDs* from modeling, in conjunction with *LM-80* luminous maintenance data, is used to project the luminous flux depreciation and lifetime at the system level. To demonstrate how it works, three types of commercial *LED* lamps are selected in this investigation. Thermal modeling is performed to predict the overall temperature distribution, to find a steady and reliable relationship between the junction point and a referenced point on the heat sink (*RBJR*). To validate the predicted junction temperature, the thermal measuring experiments using thermal transient tester (T3ster) are applied. The predicted T_j is suggested to apply on the lifetime estimation of a *LED* lamp based on the relationship between the lifetime of the *LED* package and the junction temperature. Moreover, aging test results for one lamp operating at room ambience is utilized to validate the estimated lifetime.

2. Methodology

2.1. System thermal modeling

Thermal resistance in a real lamp is extremely complex, as illustrated in Fig. 1, normally distributed in *LEDs* through packaging materials, solder joint, substrate thermal conductor, and heat sink.