Reliability Engineering and System Safety 147 (2016) 84–92

Contents lists available at ScienceDirect

Reliability Engineering and System Safety

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

An accelerated test method of luminous flux depreciation for LED luminaires and lamps

C. Qian [a,b], X.J. Fan [e,b], J.J. Fan [b,c], C.A. Yuan [a,b], G.Q. Zhang [a,b,d,*]

[a] State Key Laboratory of Solid State Lighting, Institute of Semiconductors, Chinese Academy of Sciences, Beijing 100083, China
[b] Changzhou Institute of Technology Research for Solid State Lighting, Changzhou 213161, China
[c] College of Mechanical and Electrical Engineering, Hohai University, Changzhou 213022, China
[d] EEMCS Faculty, Delft University of Technology, Delft, the Netherlands
[e] Department of Mechanical Engineering, Lamar University, Beaumont, TX 77710, USA

ARTICLE INFO

Article history:
Received 9 April 2015
Received in revised form
2 November 2015
Accepted 11 November 2015
Available online 19 November 2015

Keywords:
LED luminaire and lamp
Luminous flux depreciation
Lumen maintenance
Accelerated test
LM-80
Boundary curve

ABSTRACT

Light Emitting Diode (LED) luminaires and lamps are energy-saving and environmental friendly alternatives to traditional lighting products. However, current luminous flux depreciation test at luminaire and lamp level requires a minimum of 6000 h testing, which is even longer than the product development cycle time. This paper develops an accelerated test method for luminous flux depreciation to reduce the test time within 2000 h at an elevated temperature. The method is based on lumen maintenance boundary curve, obtained from a collection of LED source lumen depreciation data, known as LM-80 data. The exponential decay model and Arrhenius acceleration relationship are used to determine the new threshold of lumen maintenance and acceleration factor. The proposed method has been verified by a number of simulation studies and experimental data for a wide range of LED luminaire and lamp types from both internal and external experiments. The qualification results obtained by the accelerated test method agree well with traditional 6000 h tests.

1. Introduction

Compared to traditional lighting products, LED luminaires and lamps have attracted increasing attentions in general lighting market due to their high efficiency, environmental benefits and long lifetime. Unlike incandescent light sources, which display little change in light output until the bulb fails catastrophically, LED's light output degrades gradually over time [1]. Generally, useful lifetime estimates for LED lighting products are typically given in terms of the expected operating hours until light output (e.g. luminous flux) has depreciated to 70% of initial levels. The term "lumen maintenance" is often used to describe the degradation in light output during operation. Most of the commercial LED lighting products require at least 25,000 h lifetime in terms of lumen maintenance.

LM-80 has been a widely-accepted luminous flux depreciation test standard for the measurement of lumen maintenance of LED sources (such as LED package, array or module driven by an auxiliary driver) [2]. However, the test consists of a minimum of 6000 h at three different temperatures, and thus, is time-consuming and expensive to perform. With the test data provided by LM-80, TM-21 presented a method for predicting the lumen maintenance of LED light sources beyond the 6000 h [3]. TM-21 method simply uses averaged normalized lumen maintenance data and performs a non-linear regression for lifetime modeling. It cannot capture dynamic and random variation of the degradation process of LEDs. VDE standard VDE-AR-E2715-1, published and written in German, developed a so-called Border Function method for predicting the reduction in luminous flux of LEDs [4]. This method is based on the assumption that an exponential model is a conservative estimation (worst-case scenario) of the actual long term luminous flux maintenance, as it is expected that most LEDs will show the long-term luminous flux maintenance better than the assumed exponential function. Fan et al. and Wang et al., respectively, developed a degradation data-driven method to predict the lumen lifetime of high power white LEDs [5,6]. Later on, Fan et al. updated their method with the consideration of measurement error using a nonlinear filter-based approach [7]. Huang et al. applied a modified Wiener process to study the dynamic and random variations, as well as the nonlinear degradation of LEDs [8,9]. The cumulative failure distribution is obtained corresponding to different combinations of lumen

* Corresponding author at: EEMCS Faculty, Delft University of Technology, Delft, the Netherlands.
E-mail address: g.q.zhang@tudelft.nl (G.Q. Zhang).

http://dx.doi.org/10.1016/j.ress.2015.11.009
0951-8320/

maintenance degradation and color shift. Tseng and Peng previously proposed a stochastic diffusion process to model the light output degradation of LED packages [10]. With their method, the lifetime of the LED packages were estimated based on the luminous flux measurements during degradation process. Further, van Driel et al. applied this method to LM-80 data to develop an alternative statistical model to estimate lumen depreciation [11]. To sum up, all of the abovementioned studies are at component level (LED sources) and are based on the 6000 h testing data.

Color shift over time, or color stability, is another degradation concern for LEDs and LED products [12,13]. At LED source level, color shift can arise from changes in the LED package such as the emitter, phosphor used to convert emitted blue light into white light and clear encapsulant. Fan et al. proposed a nonlinear dual-exponential model to describe the chromaticity state shift process [14]. Huang et al. demonstrated that a linear model could also be applicable for the color shift of LEDs by analyzing both the experiment and simulation data [9]. However, at this time, standard methods to project LED color shift do not exist yet [1].

Development of accelerated life testing less than 6000 h is vital for successful acceptance of the LEDs and LED products. Being operated at higher stress levels than normal conditions, accelerated life tests quickly yield information on the lifetime distribution of a test unit [15,16]. The accelerated loadings in LEDs are mainly focused on thermal and moisture stresses. Tan et al. studied the degradation physics in high power white LEDs under high temperature-humidity conditions [17]. Luo et al. investigated the effects of moist environments on LED module reliability [18]. Chan et al. applied unbiased highly accelerated temperature and humidity test (HAST) to study LED package failure mechanisms [19]. Huang et al. found that during biased HAST, silicone carbonization was resulted from blue light over-absorption, which generates very high temperature inside the silicone bulk [20]. Meneghini et al. proposed a set of specific experiments, which is aimed at separately analyzing the degradation of the properties of the active layer, of the ohmic contacts and package/phosphor system in LEDs [21]. Huang et al. developed a wet-high temperature operation life test (WHTOL), and demonstrated that that lumen degradation mechanism in WHTOL is similar to the failure in LM-80 test [22]. However, these above testing conditions are not applicable to full luminaires or lamps, as a significant increase in temperature will introduce new failure modes in other components in products that are not relevant to normal operation.

At LED product level, a so-called "hammer test" was performed as a highly accelerated life tests (HALT) protocol [23]. Hammer test was not intended to be a universal accelerated life test for LED luminaires, but instead was designed solely to provide insights into potential failure modes. Furthermore, Davis et al. applied temperature and humidity accelerated life tests to understand luminaire depreciation [24]. Lall et al. focused on the accompanied light-emitting diode (LED) electrical driver's reliability under temperature and humidity accelerated test condition [25]. For the time being, Energy Star and other specifications require a minimum of 6000 h test for luminaries and lamps at room temperature for qualifications, when a full set of LM-80 data of the light source and the solder temperature (T_s) of the LED luminaires are not available [26–29].

This paper develops an accelerated test method on luminous flux depreciation of LED luminaires and lamps, to reduce the testing time from 6000 h to 2000 h. A critical element in the proposed method is to find the luminous flux depreciation "boundary curve", which is determined from a wide range of the known LM-80 data. Exponential decay model for luminous flux degradation, together with the Arrhenius acceleration model, is applied to obtain the acceleration factor. Extensive verification studies based on the internal and external test data are presented. The organization of the paper is presented as follows: Section 2 introduces the theory and methodology of the accelerated test method. Sections 3 and 4 describe the calculation of the model parameters and the accelerated test time. Sections 5 and 6 show the method verification by both numerical simulation studies and actual experiments of LED luminaries and lamps. Finally, Section 7 summarizes the concluding remarks in this research.

2. Theory and methodology

2.1. Boundary curve

The lumen maintenance is usually defined as a maintained percentage of the initial light output over time [2]. As illustrated in Fig. 1, an LED luminaire or lamp is regarded as passing the qualification test when its luminous flux maintenance stays above a specified curve, which is defined as boundary curve [30]. Therefore, the qualification accuracy for an LED luminaire highly depends on the determination of the boundary curve. Qiao et al. presented the analysis of a series of LED degradation models, and recommends the exponential decay model as an appropriate empirical model to describe the luminous flux depreciation of the LED packages and modules [31], as shown in Eq. (1) in the following

$$\Phi(t) = \beta e^{-\alpha t} \tag{1}$$

where, $\Phi(t)$ represents the normalized luminous flux at the time t, β and α are the pre-factor and depreciation rate respectively. In this study, the boundary curve is expressed by Eq. (1). When the $\Phi(t)$ is normalized by the initial value and the parameter β equals to unity. Meanwhile, the boundary curve passes the point (L_{70} corresponding to Φ of 70%), where L_{70} indicates the lifetime t with respect to the 70% lumen depreciation. For example, if L_{70} equals 25,000 h, the degradation rate α is then calculated to be 1.427e-5 from Eq. (1). Based on this curve, $L_{91.8}$ is equal to 6000 h. This implies that at 6000 h, the lumen maintenance is reduced to 91.8%. This is what the Energy Star Program requires [26,27].

Previous studies show that temperature plays a significant role on the luminous flux depreciation of LED luminaires [1,3]. It is possible to describe the temperature dependency by an Arrhenius model at luminaire level

$$\alpha = \mathrm{A}e^{-\frac{E_a}{kT_s}} \tag{2}$$

where, A and E_a are the pre-factor and activation energy respectively, k is the Boltzmann constant (i.e. 8.617385×10^{-5} eV/K) and T_s stands for the solder temperature in Kelvin. The activation energy is defined as "equivalent activation energy" due to the complexity of an LED luminaire or lamp system. Furthermore, the relationship of lumen maintenance between a luminaire and its light source can be expressed as follows [29]

$$\Phi_l(t) = \Phi_p(t) \times C(t) \tag{3}$$

where $\Phi_l(t)$ and $\Phi_p(t)$ indicate the lumen maintenance of a LED luminaire and its light source respectively. And $C(t)$ is the correlation function in terms of the time t. Assuming that both $\Phi_l(t)$ and $\Phi_p(t)$ follow Eq. (1), the correlation function $C(t)$ can be solved as:

$$C(t) = \frac{\beta_l}{\beta_p} exp(-\Delta\alpha t) \quad \text{where} \quad \Delta\alpha = \alpha_l - \alpha_p \tag{4}$$

where β_l and β_p and α_l and α_p are pre-factors and depreciation parameters for a LED luminaire (or lamp) and its light source, respectively. The parameter $\Delta\alpha$ determines the relationship of luminous flux depreciation rates between the LED luminaire and its light source. A positive $\Delta\alpha$ indicates that the luminous flux depreciation rate of a LED luminaire is faster than that of its light