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New method of online testing and data processing for LED lamps

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Abstract: In order to achieve quick and accurate lifetime prediction of LED lighting products under the testing time of 2 000 h, a method of online testing of luminous flux is proposed under the condition of temperature stress. Exponential fitting of lumen maintenance, the Bayesian estimation of failure probability, the Weibull distribution of lifetime and the Arrhenius model of the decay rate are used in combination to acquire the distribution of failure probability over time at the ambient temperatures of 25 ℃. The lifetime test of the same lamps based on the Energy Star standard under the testing time of 6 000 h is also implemented to verify the effectiveness of the method. The errors of lifetimes acquired with the proposed method are 7%, 4%, 3% and 1% at the failure probabilities of 62.3%, 10%, 5% and 1%, respectively.

Key words: online testing; accelerated test; Bayesian estimation; reliability analysis

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With the vigorous implementation of the plan of banning incandescent lamps in the global scale, LED products are widely used in various lighting fields. While their advantages in energy conservation and environmental protection have been widely admitted, their long lifetime and good reliability are still being questioned. As a consequence, the quick and accurate prediction method of lifetime and reliability for LED products has become a new research focus[1-4]. The test and calculation method for a LED products are reported by the IES LM-79[5], IES LM-84[6] and IES TM-28[7] standards, and the test time is at least 6 000 h under the ambient temperature of 25 ℃. The test and calculation method under three different case temperatures for a LED light source are reported by the IES LM-80[8] and IES TM-21[9] standards, and the test time is also at least 6 000 h under the ambient temperature of 25 ℃. Clearly, the test time of 6 000 h recommended by above standards restricts the replacement rate of LED products, and, therefore, various methods of accelerated aging test of the LED were proposed.

Koh et al. [10-12] reported the accelerated aging test which was achieved by increasing the stress conditions including temperature, humidity and current. Tan et al. [13] reported the accelerated aging test of the LED package at the ambient temperature of 85 ℃, and the humidity of 95%, 85% and 70%, respectively. Cai et al. [14] reported the accelerated aging method of the LED package at the ambient humidity of 85%, and the ambient temperature of 65, 85 and 95 ℃, respectively. Tang et al. [15] reported a step-stress accelerated aging test for the LED light source module at the ambient temperature of 45, 65 and 85 ℃. Ren et al. [16] reported several step-stress accelerated aging tests for the LED light source module at the ambient temperature of 45, 85 and 95 ℃. In their experiments, the luminous flux measurement was also under the ambient temperature of 25 ℃. It is well known that the lumen maintenance of LED products obeys the negative exponential law under its operating temperature[17]. Whether the law is still effective for luminous flux measured at a temperature different from its working temperature, remains to be seen, and to the best of our knowledge, no experiment has been carried out yet.

1 Related Work

In this paper, a new method of accelerated aging test of LED lamps is proposed. The lamps are respectively measured at the ambient temperatures of 60 and 80 ℃, and the luminous flux is online testing, which means that luminous flux is measured at its working temperature. Thus, the lumen maintenance strictly meets the requirement of negative exponential law. In the analysis and processing of the experimental data, the Bayesian estimation[15] and the Weibull distribution[13-14] of the failure probability of lamps are used in combination. Ultimately, the activation energy is calculated according to the Arrhenius model, and the lifetime of LED lamps at the ambient temperature of 25 ℃ is obtained.

2 Theory Model

The lumen maintenance of LED lamps meets the expo-

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nential decay law, that is

$$\frac{\Phi_t}{\Phi_0} = \exp(-\beta_T t) \tag{1}$$

where Φ_t/Φ_0 is the lumen maintenance; β_T is the decay rate at the junction temperature T; and t is the testing time. According to Eq. (1), it is clear that the lumen maintenance should be measured at the working temperature rather than a fixed temperature of 25 ℃. When $\Phi_t/\Phi_0 = 0.7$, the time t is considered to be the lifetime of LED product, namely,

$$t = -\frac{\ln 0.7}{\beta_T} \tag{2}$$

The decay rate β_T of the LED satisfies the Arrhenius model, which is a function of the junction temperature:

$$\beta_T = A\exp\left(\frac{-E_a}{KT}\right) \tag{3}$$

where A is a constant; E_a represents the activation energy; K is Boltzmann's constant.

The lifetime of the LED is consistent with the Weibull distribution[17-18]:

$$F(t) = \hat{F}_{iB} = 1 - \exp\left(-\frac{t}{\eta}\right)^m \tag{4}$$

where $F(t)$ is the failure probability; m is the shape parameter; and η is the characteristic lifetime. $F(t)$ can be calculated by the Bayesian estimation method.

According to the Bayesian statistics[19], the posterior probability density of the lifetime for the i-th failure lamp can be calculated by the samples information together with priori information:

$$h(F_i \mid r_i) = \frac{L(r_i \mid F_i)\pi(F_i)}{\int_0^1 L(r_i \mid F_i)\pi(F_i)\,\mathrm{d}F_i} \qquad i = 1, 2, \ldots, 7 \tag{5}$$

where $h(F_i \mid r)$ is the posterior probability density of failure probability; r_i represents the number of failure in the i-th group; $L(r_i \mid F_i)$ is the likelihood function of samples; and $\pi(F_i)$ is the priori probability density function of failure probability. Their expressions are[18]

$$\left.\begin{aligned} L(r_i \mid F_i) &= C_{s_i}^{e_i} F_i^{e_i}(1 - F_i)^{s_i - e_i} \qquad 0 < F_i < 1 \\ \pi(F_i) &= \iint_D \pi(F_i \mid a, b)\pi(a, b)\,\mathrm{d}a\mathrm{d}b \end{aligned}\right\} \tag{6}$$

where s_i is the number of samples which is seven in this experiment and e_i is the number of cumulative failures.

$$e_i = \sum_{j=1}^{i} r_i \qquad i = 1, 2, \ldots, 7 \tag{7}$$

$\pi(F_i \mid a, b)$ is the beta distribution and $\pi(a, b)$ is the prior distribution of two ultra parameters of a and b. Their expressions are

$$\left.\begin{aligned} \pi(F_i \mid a, b) &= \frac{F_i^{a-1}(1 - F_i)^{b-1}}{B(a, b)} \\ \pi(a, b) &= \frac{1}{c - 1} \qquad 0 < a \leqslant 1, 1 < b < c \end{aligned}\right\} \tag{8}$$

where $B(a, b)$ is the beta function and it is expressed as

$$B(a, b) = \int_0^1 t^{a-1}(1 - t)^{b-1}\mathrm{d}t \tag{9}$$

The proposed value of c is recommended four[19]. The Bayesian estimation $\hat{F}_{iB}(a, b)$ of F_i is

$$\hat{F}_{iB} = \int_0^1 h(F_i \mid r_i)F_i\mathrm{d}F_i \tag{10}$$

Combined with the above equations, the least square method is used to fit the curves of the failure probability over the failure time, and the shape parameters and characteristic lifetime of the Weibull distribution can be then calculated.

3 Accelerated Aging Experiments of Online Testing and Data Processing

3.1 Accelerated aging experiments of online testing

Fig. 1 is the online testing platform of accelerated aging test for LED lamps. The thermostat box, integrating sphere of 0.5 m of Labsphere and spectral radiometer are used in combination to give luminous flux through the real-time and online testing. LED lamps are placed on a rotary shelf of multi-position. Controlling and rotating the shelf by the command through the computer causes the LED lamp to turn to the test window which is 20 mm in diameter with a high transmittance of glass. Then luminous flux and other parameters can be tested through the external integrating sphere.

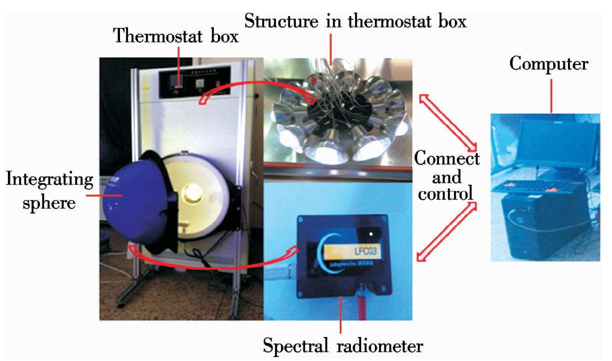

Fig. 1 The online testing platform of accelerated aging for LED lamps

In this experiment, the temperatures of thermostat box are set to be 60 and 80 ℃, respectively. Seven LED lamps (chip of ES, green phosphor of Nakamura-Yuji and red phosphor of Grirem, potting glue of 6630 and patch glue of DX20C, and driver of Lide) are the test samples. The correlated color temperatures of these lamps are between 3 500 to 3 580 K. Data acquisition frequency is once every 24 h. For each acquisition, the rotary shelf rotates eight laps to obtain eight time measurements, and the averaged luminous flux is then obtained. Fig. 2 shows the change of lumen maintenance in 1 800 and 1 464 h at 60 and 80 ℃, respectively. The different lines represent different lamps and the number of lines is seven. It can be seen that the lumen maintenance is approximately 91% and 92%, respectively.

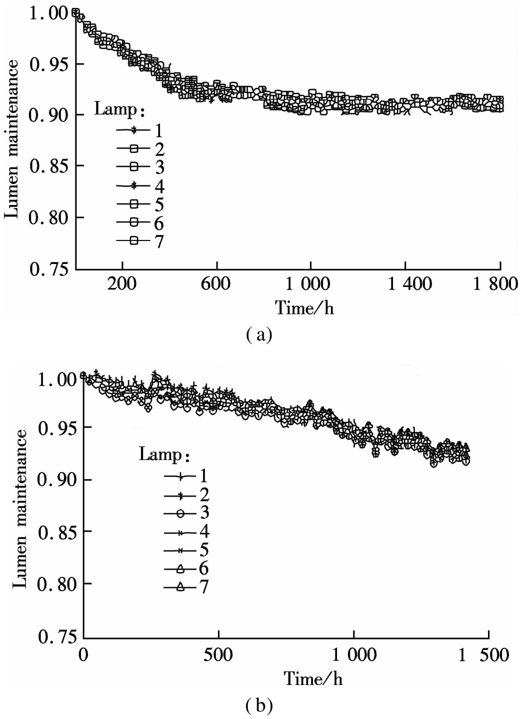

Fig. 2 The change of lumen maintenance at different temperatures. (a) 60 ℃; (b) 80 ℃

3.2 Data processing at the accelerated temperature

In order to calculate the decay rate β_T of each lamp, the least square method is used to perform the negative exponential fitting by the data in Fig. 2. The lifetime at two temperatures are then calculated according to Eq. (2). Tab. 1 gives the results of the accelerated lifetime at two temperatures, where $t_{60\ ℃}$ and $t_{80\ ℃}$ represent the failure time at 60 and 80 ℃, respectively. Lifetime is arranged from small to large. It can be seen that the accelerated lifetime at 60 ℃ is almost twice that at 80 ℃.

Tab. 1 Accelerated lifetimes at two temperatures h

Lamp	1	2	3	4	5	6	7
$t_{60\ ℃}$	9 199	9 255	9 260	9 998	10 270	10 758	11 620
$t_{80\ ℃}$	5 053	5 075	5 183	5 816	6 052	6 182	6 964

Tab. 2 gives the calculation results of the failure probability in detail. It can be seen that the failure probability increases as the number of cumulative failures increases.

Tab. 2 The calculation results of failure probability for LED lamps %

Lamp	1	2	3	4	5	6	7
$\hat{F}_{iB}$	15.0	25.1	35.2	45.3	55.4	65.5	75.6

The least square method is used to fit the curves of the failure probability over the failure time, and the shape parameters and characteristic lifetime of the Weibull distribution are then calculated, as shown in Tab. 3. It can be seen that the characteristic lifetimes are, respectively, 10 820 and 6 345 h at the ambient temperatures of 60 and 80 ℃, and the correspondent shape parameters are 7.792 4 and 5.836 0, respectively.

Tab. 3 The parameters of lamps

Temperature/ ℃	Characteristic lifetime/h	Shape parameters
60	10 820	7.792 4
80	6 345	5.836 0

3.3 Lifetime data processing at room temperature

In this experiment, the junction temperatures of the LED samples are actually measured by means of spectral analysis[20], which are 373.15 K(T_{j1}) and 388.15 K(T_{j2}) at the ambient temperature of 60 and 80 ℃, respectively. According to Eq. (3), the activation energy is deduced and calculated by

$$E_a = \frac{K\ln(L_{60}/L_{80})}{\dfrac{1}{T_{j1}} - 1/T_{j2}} = 0.444\ \text{eV} \tag{11}$$

The lifetime of LED products at the ambient temperatures of 25 ℃ is then calculated as

$$L_0 = L_i \exp\left[\frac{E_a}{k}\left(\frac{1}{T_0} - \frac{1}{T_i}\right)\right] \tag{12}$$

where L_0 is the lifetime at 25 ℃; L_i is the accelerated lifetime; T_i is the junction temperature under an accelerated condition and T_0 is the junction temperature at the ambient temperatures of 25 ℃. T_0 is actually measured, and it is 348.15 K. With the activation energy of 0.444 eV and Eq. (10), the lifetime of the seven LED lamps is calculated at the ambient temperature of 25 ℃, from the accelerated lifetime data either at 60 ℃ or at 80 ℃ in Tab. 1. The results are listed in Tab. 4. Then the parameters of the Weibull distribution at 25 ℃ are calculated by the use of the least square method, and the corresponding failure probability distribution as a function of time is acquired. The red curve in Fig. 3 shows the acquired curve with the

Tab. 4 Deduced lifetime at the room temperature with the activation energy of 0.444 eV for LED lamps

Lamp	60 to 25 ℃	80 to 25 ℃
1	24 795	23 223
2	24 946	23 225
3	26 949	23 821
4	27 682	26 730
5	28 997	27 815
6	31 321	28 412
7	31 918	32 006
Characteristic lifetime	29 164	29 162

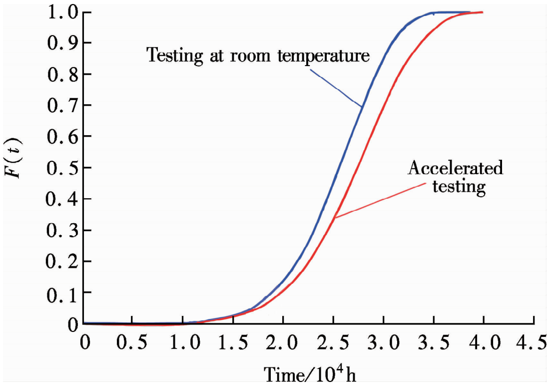

Fig. 3 The failure probability distributions over time

data in the fourth column. It can be seen that the characteristic lifetimes are respectively 29 200, 19 800, 17 500 and 13 300 h at the failure probabilities of 62.3%, 10%, 5% and 1%.

4 Reliability Analysis

To verify the accuracy of this test method, we implement the lifetime test of the same type of lamps based on Energy Star standard which is a 6 000 h aging test at the ambient temperature of 25 ℃. According to the standard, the data in the first 1 000 h should be excluded due to its relatively large fluctuations. Fig. 4 shows the change of lumen maintenance after 1 000 h. Again, in order to calculate the decay rate and lifetime for each lamp, the least square method is used to perform the negative exponential fitting.

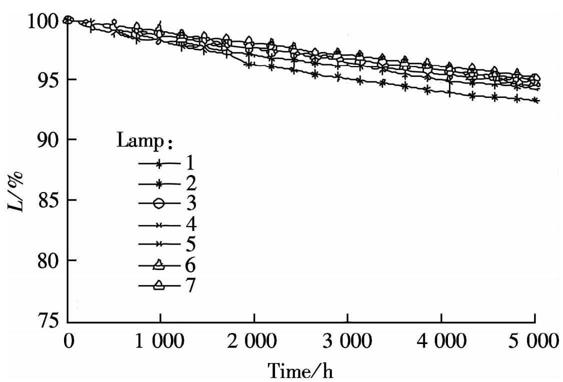

Fig. 4 The change of lumen maintenance at 25 ℃

By the Bayesian estimation method, the failure probabilities of the seven lamps are calculated. Tab. 5 gives the calculation results of decay rates, failure time and failure probabilities, where $t_{25\,℃}$ is the failure time at the ambient temperature of 25 ℃. The least square method is used to fit the curve of the failure probability over time to obtain the characteristic lifetime and shape parameters of the Weibull distribution. The acquired characteristic lifetime is 27 257 h and the shape parameter is 6.368 7. The curves in Fig. 3 represent the Weibull distribution curves. It can be seen that at the failure probabilities of 62.3%, 10%, 5% and 1% correspond to the lifetime of 27 200, 19 100, 17 000 and 13 200 h. In a comparison with the curve of the test under the room temperature, the errors of lifetime acquired by the proposed method are 7%, 4%, 3% and 1%, respectively.

Tab. 5 The corresponding parameters for LED lamps

Lamp	1	2	3	4	5	6	7
$\beta_T/10^{-5}$	1.76	1.48	1.48	1.33	1.27	1.26	1.18
$t_{25\,℃}$/h	20 161	23 945	24 086	26 877	28 043	28 243	30 206
e_i	1	2	3	4	5	6	7
$\hat{F}_{iB}$/%	15.0	25.1	35.2	45.3	55.4	65.5	75.6

5 Conclusion

Under the conditions of temperature stress, an online testing method of luminous flux of LED lamps is proposed. Seven LED lamps are used to conduct the test, and the accelerated aging test is done at the ambient temperature of 60 and 80 ℃, respectively. Then the lifetime of the failure probability at the ambient temperature of 25 ℃ is deduced from the data at accelerated temperatures. To verify the effectiveness of the proposed method, the standard aging test of the same type of lamps at the ambient temperature of 25 ℃ recommended by Energy Star is implemented. Compared with the standard method, the errors of lifetimes acquired are 7%, 4%, 3% and 1% at the failure probabilities of 62.3%, 10%, 5% and 1%, respectively. The online testing method greatly reduces the test time and improves the stability of data acquisition and test accuracy. The luminous flux is measured at working temperature by this method, which strictly meets the requirements of the negative exponential law of lumen maintenance. It can increase the accuracy of the calculation results. The experiments and the reliability platform provide some guidance for other online testing, and the calculation result can be a reference for the same type of LED lamps.

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LED 灯具在线测试和数据处理的新方法

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摘要：为实现 LED 照明产品寿命及其可靠性的快速准确预测，在测试时间为 2 000 h 和温度应力的条件下，提出了一种加速老化的在线测量光通量的方法. 结合使用光通维持率的指数模型、失效概率的贝叶斯估计、威布尔分布和阿伦纽斯模型，以获取 25 ℃条件下的失效概率分布. 同时，采用能源之星 LM-79-08 标准推荐的常温下 6 000 h 测量方法对相同的产品进行寿命验证. 结果表明：当失效概率为 62.3%，10%，5% 和 1% 时，所提计算方法得到的寿命误差分别为 7%，4%，3% 和 1%.

关键词：在线测试；加速测试；贝叶斯估计；可靠性分析

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