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The Influence of Junction Temperature Variation of LED on the Lifetime Estimation During Accelerated Aging Test

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ABSTRACT In this paper, seven LED lamps are selected to investigate how the junction temperature (Tj) of LED varies during the step-stress temperature accelerated aging test. The ambient temperatures are 80 °C and 70 °C for the first and second step of the aging test, respectively, and the total aging time is 2180 h. A non-contact method for monitoring junction temperatures of samples, by the ratio of white light energy to blue light energy (W/B), is applied. Experimental measurements show that the W/B ratio and Tj satisfy good linear relationship during the aging for all samples. Then, the junction temperatures are acquired at eight typical points of aging time which are used to eliminate the impact of Tj variation on the estimation of the decay rate and accelerated lifetime. It is shown that the estimated lifetime is longer than that acquired by the traditional method. The estimation errors of the accelerated lifetimes by the traditional method are in a range from 12.8% to 18.6% under the aging temperature of 80 °C and from 12.5% to 20.3% under the aging temperature of 70 °C for the seven samples. The estimation accuracy of the decay rates and accelerated lifetimes of LED lamps in the step-stress accelerated aging test is improved by the proposed methodology to a certain extent.

INDEX TERMS Life testing, lifetime estimate, light emitting diodes.

I. INTRODUCTION

In recent years, various types of LED lamps characterized as low power dissipation, long lifetime and stable brightness develop rapidly to occupy the main market of household lamps. However, the commonly standard for LED aging test is IESLM-79 [1], which the testing time is proposed to be 6000 hours under aging temperature of 25°C. In order to shorten the testing time, Zhang et al. proposed an accelerated aging method which the testing time lasted for 1300 hours under aging temperature of 55°C [2]. Qian et al. proposed a method which the testing time was 2000 hours and the aging temperature was 55°C [3]. At present, a mature method of accelerated aging test for LED is to use two groups of samples of the same product and to age them at two different high-temperatures [4]–[7]. According to the decay rates of the accelerated lifetimes under the two conditions, the activation energy of the LED can be calculated and the lifetime under normal ambient temperature can be then obtained by the Arrhenius model. This method however requires higher consistency of the two groups of samples. Liao and Tseng [8], Tang *et al.* [9], and Hu *et al.* [10] proposed a methodology of step-stress accelerated aging test for LED. They exerted two different temperature stresses to the same group of LED samples sequentially in the aging test, and used the Nelson model to obtain the decay rates and the accelerated lifetimes for the aging under the second temperature stress.

In accelerated aging test, the variation of junction temperature (i.e. Tj temperature) is an important parameter affecting the lifetime estimation. It is because the accelerated lifetime estimation is based on the lumen maintenance of LED conforming to the exponential decay law in aging time and the decay rate related to Tj is supposed to be constant [4], [11], [12]. It is known that as the junction temperature increasing, the luminous flux of LED decreases. Therefore the luminous maintenance of LED during aging period relates not only to the aging of LED itself, but also to the variation of Tj. The Tj has independent influence on the luminous fluxes during the aging process. To satisfy the exponential decay law of lumen maintenance, the measurement values of the luminous fluxes should be modified by eliminating the effect of Tj variations.

Ke *et al.* [13] investigated the Tj variation of white LED during an aging test of 6000 hours. The junction temperatures of LED at different stages were measured by voltage method and the measurement values of luminous fluxes were modified according to Tj variation. Then they obtained the corrected lifetime estimation of the LED. The voltage method was developed by Dragoljub in 1993 [14], which was considered to be the most accurate method for Tj measurement. However, it is a contact method for Tj monitoring which is only applicable to LED modules.

In the study of non-contact measurement of junction temperature of white LED, Tamura *et al.* [15] discovered that the power of LED chip and phosphor decay with different rate as Tj increasing. Ye *et al.* [16], [17] proved the functional relationship of Excitation efficiency and Tj, which could be used for Tj measurement. Hisashi *et al.* [18] proposed a model that the ratio of yellow light energy to blue light energy (Y/B) was related to the Tj of white LED. Narendran *et al.* [19] and Gu and Narendran [20]carried out the further studies on the spectrum method, in which they proposed a linear relationship between Tj of white LED and the ratio of white light energy to blue light energy (W/B), and then the Tj could be obtained by the measurement of spectrum power distribution (SPD) of the LED. Chen and Hui [21] applied the method on white LED to measure the linear relationship between Tj and W/B ratio with the R-squares all greater than 0.99. However, the effectiveness of Tj measurement either by W/B ratio or by Y/B ratio, refers to the initial un-aged white LED samples only, and whether it is still effective for the aged white LED lamps has not been proven, to the best of our knowledge.

In this paper, the influence of Tj variation of white LED lamps on the estimation of the decay rate and accelerated lifetime during step-stress accelerated aging test is studied. Seven samples were aged under temperature stresses of 80°C and 70°C sequentially, with the aging time of 980 and 1200 hours respectively. At different stage of the aging test, the relationship between Tj and W/B ratio is experimentally established, which is then used to acquire the Tj value of the lamp at that stage. The measurement values of luminous maintenance are modified by eliminating the impact of the variation of Tj, and the decay rate and accelerated lifetime are then estimated. The results show that the estimation accuracy by the proposed method is improved to a certain extent as compared with that by traditional method.

II. THEORETICAL ANALYSIS

During the aging test of LED products, the luminous flux satisfies the exponential decay law [11], [12]:

$$\Phi_t = \Phi_0 \times e^{(-\beta t)} \tag{1}$$

where Φ_0 is the initial luminous flux, t is the aging time, Φ_t is the lumen flux at time of t, Φ_t/Φ_0 is the luminous maintenance and β is the decay rate. The lifetime of LED is usually defined as the aging time when the luminous maintenance reduces to 70%. The lifetime of τ can be then written as:

$$\tau = -\frac{\ln(\Phi_t/\Phi_0)}{\beta} = -\frac{\ln(0.7)}{\beta} \tag{2}$$

The decay rate of β correlates with junction temperature of Tj, and according to Arrhenius model it can be expressed as [22]–[25]:

$$\beta_{Tj} = A \times e^{(-E_a/kTj)} \tag{3}$$

where A is a constant related to the failure mode and the type of accelerated aging of the LED sample, E_a represents the activation energy, Tj is the junction temperature and k is Boltzmann's constant which is 8.6171×10-5eV/°C. Obviously, the activation energy of E_a can be calculated by the decay rates at two different junction temperatures which is useful for the lifetime estimation of the products under normal working temperature.

For the step-stress accelerated aging test the decay rates and the accelerated lifetimes of the samples at the second step of the aging test cannot be simply calculated by (1), because the samples have been aging for a certain time at the first step of the aging test, and the result of the first step is the initial luminous flux of the second step. In this case the cumulative failure model of products proposed by Nelson is adopted. Suppose a LED lamp is aged for t_1 hours under temperature stress of Tj_1 in the first step of accelerated aging test. According to Nelson model, the cumulative amount of luminous flux degradation of the product, $\Phi_1(t_1)$, is equal to that aged for t_1' hours under temperature stress of Tj_2 in the second step of accelerated aging test, $\Phi_2(t_1')$. That is:

$$\Phi_2\left(t_1'\right) = \Phi_1\left(t_1\right) \tag{4}$$

where t_1' is an equivalent aging time under Tj_2. Substituting (1) into (4), we have:

$$\beta_2 t_1' = \beta_1 t_1 \tag{5}$$

The total aging time of the LED lamp under second step of accelerated aging test of t_2' is the sum of actual aging time of t_2 and the equivalent aging time of t_1'. Combining with (5) we have:

$$t_2' = t_2 + t_1' = t_2 + \frac{\beta_1}{\beta_2} t_1 \tag{6}$$

Substituting (6) into (1), we have:

$$\Phi_2 = \Phi_0 e^{(-\beta_1 t_1)} \times e^{(-\beta_2 t_2)} \tag{7}$$

The data processing procedure of the step-stress accelerated aging test is as follows. Firstly, the decay rate of β_1 and accelerated lifetime in the first step of the aging test are obtained by fitting the luminous maintenances in this stage with (1). Then the decay rate of β_2 and accelerated lifetime in the second step of the aging test, along with the acquired value of $\beta_1 t_1$, are obtained by fitting the luminous maintenances in the second step of the aging with (7).

During accelerated aging test the luminous fluxes are measured with an integrating sphere connected to a spectrometer under the ambient temperature of 25°C. During accelerated aging test, the junction temperature increases gradually over aging time [13] and the variation of junction temperature also brings about luminous flux degradation independently. To satisfy the exponential decay law of the luminous maintenance, the measurement value of luminous flux should be modified by eliminating the impact of Tj variation. Suppose the junction temperature increases from initial Tj_0 to Tj_t under ambient temperature of 25°C as the LED sample has been aging for t hours. The increased junction temperature causes an approximately linear decrease of the luminous flux of the LED [13]:

$$\Delta\Phi = \mu \Delta Tj \tag{8}$$

where $\Delta Tj = Tj_t - Tj_0$ and μ is a negative constant with unit of lumen/ °C. Suppose after an aging time of t, the measurement value of luminous flux is Φ_t and the corrected result considering the decrement of luminous flux given in (8) is Φ'_t. Then we have [13]:

$$\Phi'_t = \Phi_t - \mu\,(Tj_t - T_0) = \Phi_t + \Delta\Phi_t \tag{9}$$

In this paper, the junction temperatures of samples of LED lamps during the accelerated aging test are measured with so-called W/B-Tj method. The spectrum of white LED can be separated into two parts [26]. The left part is mainly the chip spectrum, the blue-light spectrum, and the right part is mainly the phosphor spectrum. It has been shown that the value of W/B ratio is linearly proportional to the junction temperature of the LED:

$$W/B = a \times Tj + b \tag{10}$$

where a and b are constant parameters with the unit of a being 1/°C. Using W/B ratio to acquire the junction temperature of LED sample after t hours of aging, the parameter values have to be determined firstly. This is done by applying pulse current to the sample and measuring the chromaticity parameters simultaneously at different ambient temperatures. In this measurement, as the pulse time of the power supply is very short, the heat generated by LED itself can be neglected and the junction temperature of the sample is equal to the ambient temperature. Thus the relationship between W/B ratio and Tj in (10) can be established by a linear fitting of the experimental data. Then the junction temperature of the sample keeping in normal working state under ambient temperature of 25°C can be obtained with the established relationship and the value of W/B ratio in this situation.

III. EXPERIMENTS

We randomly selected seven white LED bulbs as samples, which contain two kinds of phosphors as yellow phosphor: $Y_3Al_5O_{12}$:Ce and red phosphor: $CaAlSiN_3$:Eu. In order to avoid the interference to the measurement caused by the aging of the driving chip, the driving chips are not installed when the lamps are packaged. The power supply is 134mA DC.

A. MEASUREMENT OF LUMINOUS FLUX AND CHROMATICITY PARAMETERS

The high-temperature accelerated aging and testing platform is shown in fig.1, where (a) is the high-temperature box for sample aging and the luminous flux measurement system, and (b) is the W/B-Tj measurement system. Before the aging progress, the applied temperature level has been determined by calculating the failure possibility under different temperature stress [27]. The safe temperature for decay mechanisms of LED is lower than 100°C. So the box temperature is set to be 80°C and 70°C sequentially for the step-stress accelerated aging. In the progress of step stress aging test, the aging times are of 980 and 1200 hours respectively. The luminous flux measurement system includes an integrating sphere with diameter of 1.5 meter and Labsphere usb-2000 spectrometer placed in an incubator, as shown in fig.1 (a). The wavelength range of the measurement system is from 350nm to 1000nm and the fluctuation of luminous flux measurement is less than 0.1% within 24 hours. The W/B-Tj measurement system is composed of a high-temperature box, an integrating sphere

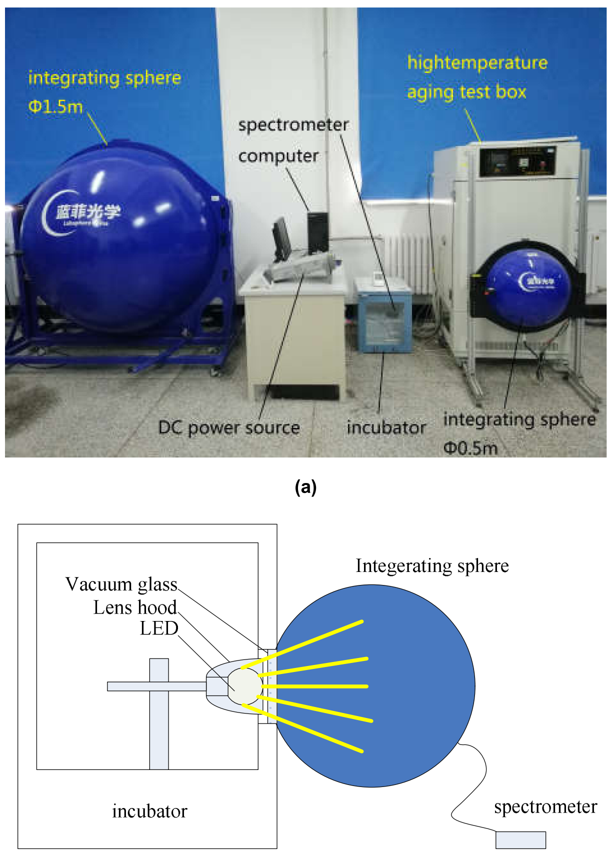

FIGURE 1. High-temperature accelerated aging and testing platform. (a) Luminous flux measurement system. (b) W/B-Tj measurement system.

with diameter of 0.5 meter and the spectrometer. The opening of the integrating sphere is butted with the window of the high-temperature box, as shown in fig.1 (b).

At the measurement stage after certain aging time, all the samples are cooled under ambient temperature of 25°C firstly. Then the sample is put into the integrating sphere of diameter of 1.5 meter, one by one, for the measurements of luminous flux and chromaticity parameters. The sample is in stable working state and the ambient temperature is 25°C in the measurements. The W/B ratio is calculated by acquired chromaticity parameters.

B. W/B-Tj MEASUREMENT

For the W/B-Tj measurement after a certain aging time, an LED sample is firstly cooled under ambient temperature of 25°C and then placed in the high-temperature box with temperature set at 40°C. After 20 minute heating to achieve stable state, the sample is lighted with DC pulse current of 134mA and the chromaticity parameters are simultaneously measured. The junction temperature can be considered to be the set temperature of 40°C and the W/B ratio under this temperature is obtained. The measurement system is shown in fig.1 (b). Repeating above procedure with the temperature set at 50°C, 60°C, 70°C, 80°Cand 90°C in turns, the relationship between W/B ratio and Tj is established.

C. MEASUREMENT OF PARAMETER μ FOR LUMINOUS FLUX MODIFICATION

Before the accelerated aging process, the values of μ in (8) for the samples should be experimentally obtained with the measurement system shown in fig.1 (b). The sample is put into the high-temperature box with the temperature set at 40°C, 50°C, 60°C, 70°C, 80°C and 90°C in turns. The sample is lighted with DC pulse current of 134mA and the partial luminous flux radiating into the integrating sphere is simultaneously measured. Again, the junction temperature of the sample can be considered to be the temperature inside the box. The acquired partial luminous flux of the sample at each junction temperature can be converted into full luminous flux by an advanced investigation. Then the variation of luminous flux of the sample is acquired, and the value of μ can be obtained by a linear fitting of the data.

IV. EXPERIMENTAL RESULTS

A. THE μ VALUES

The parameters of μ for the samples are measured before the accelerated aging test. Table 1 lists the luminous flux of the LED samples at different junction temperatures. With the data in table 1, the linear fittings of luminous flux as junction temperature for the samples are obtained and shown in fig.2. The correspondent fitting formulas are listed in table 2. It can be seen that all the R-squares of the fittings are higher than 0.99, indicating a good linear relationship between luminous flux and Tj. It also can be seen that the μ values are in a range from -1.85968 to -2.23990. However, our research shows that the change of μ value for the same sample during the accelerated aging test is small and can be neglected.

TABLE 1. Luminous flux at different Tj (lumen).

Tj	LED1	LED2	LED3	LED4	LED5	LED6	LED7
40℃	522	520	527	524	522	514	524
50℃	507	501	508	511	503	489	506
60℃	488	484	485	487	485	477	486
70℃	469	466	463	467	467	457	467
80℃	451	445	443	447	450	436	448
90℃	428	425	415	430	429	414	427

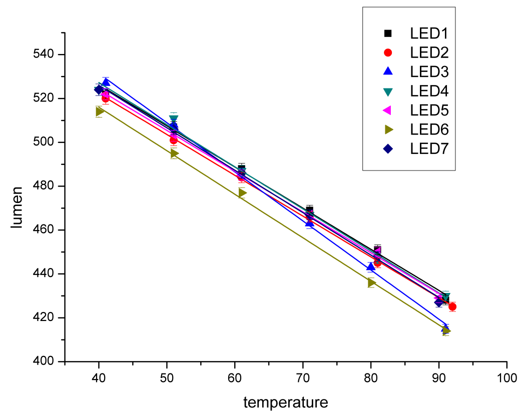

FIGURE 2. Linear fittings of luminous flux as Tj for samples.

TABLE 2. Relationship between luminous flux and Tj.

	relationship	μ	R-square
LED1	L=-1.87714Tj+601.39143	-1.87714	0.99614
LED2	L=-1.86219Tj+596.71513	-1.86219	0.99907
LED3	L=-2.23990Tj+620.96029	-2.23990	0.99801
LED4	L=-1.91930Tj+604.02036	-1.91930	0.99295
LED5	L=-1.85968Tj+598.42871	-1.85968	0.99791
LED6	L=-1.98572Tj+595.47778	-1.98572	0.99750
LED7	L=-1.93472Tj+603.37971	-1.93472	0.99736

B. W/B RATIO VERSUS Tj

By the end of the test, an unaged lampshade and an aged lampshade are fixed on a LED module in turn to calculate the deviation of W/B ratio between the two cases. The W/B ratio with the unaged lampshade is 5.7683, and it is 5.7726 with the aged lampshade. The deviation is less than 0.075%, and so it can be neglected. The variations of W/B ratio as junction temperature of LED samples at eight typical points of the aging time are acquired, and then the linear fittings given by (10) are obtained. Table 3 lists the values of the parameters and the R-square values of the linear fittings for each sample. It can be seen that most of the linear fittings have R-square values exceeding 0.98. The data indicates that during the accelerated aging test, the W/B ratio and the junction temperature have a good linear relationship all the time for all samples. Fig.3 shows the linear fittings of W/B ratio as Tj for

TABLE 3. Parameter of relationship between W/B and Tj (unite of *a* : 1/°C).

	time	0 hr	360 hr	720 hr	980 hr	1320 hr	1560 hr	1820 hr	2180 hr
	$a\ (10^{-3})$	-8.99	-8.46	-7.85	-7.76	-7.54	-7.36	-7.27	-6.76
LED1	b	6.265	6.141	6.048	5.959	5.873	5.798	5.631	5.512
	R-square	0.992	0.996	0.997	0.981	0.992	0.997	0.991	0.992
	$a\ (10^{-3})$	-9.01	-8.43	-7.92	-7.81	-7.68	-7.47	-7.39	-6.86
LED2	b	6.167	6.064	5.933	5.903	5.810	5.623	5.517	5.397
	R-square	0.997	0.990	0.998	0.990	0.980	0.994	0.980	0.993
	$a\ (10^{-3})$	-9.58	-8.94	-8.67	-8.36	-7.96	-7.74	-7.53	-7.06
LED3	b	6.223	6.179	6.032	5.924	5.869	5.744	5.628	5.455
	R-square	0.994	0.981	0.985	0.996	0.992	0.991	0.987	0.993
	$a\ (10^{-3})$	-9.16	-8.69	-8.16	-7.89	-7.64	-7.39	-7.13	-6.79
LED4	b	6.248	6.197	6.083	5.977	5.901	5.798	5.687	5.567
	R-square	0.998	0.993	0.990	0.982	0.989	0.973	0.998	0.993
	$a\ (10^{-3})$	-9.00	-8.51	-8.20	-7.88	-7.50	-7.36	-7.16	-6.54
LED5	b	6.281	6.203	6.110	6.024	5.913	5.805	5.778	5.540
	R-square	0.995	0.989	0.990	0.993	0.997	0.994	0.988	0.985
	$a\ (10^{-3})$	-9.98	-9.64	-8.86	-8.46	-8.17	-7.81	-7.59	-7.11
LED6	b	6.254	6.143	6.057	5.969	5.874	5.764	5.614	5.484
	R-square	0.996	0.998	0.984	0.995	0.969	0.963	0.988	0.976
	$a\ (10^{-3})$	-10.01	-9.28	-8.43	-8.02	-7.70	-7.58	-7.34	-6.87
LED7	b	6.250	6.148	6.069	5.971	5.790	5.687	5.577	5.400
	R-square	0.988	0.988	0.994	0.994	0.984	0.969	0.995	0.980

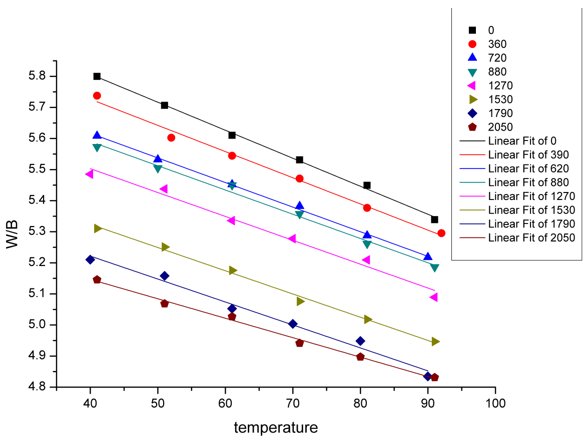

FIGURE 3. Linear fittings of W/B ratio as Tj at different points of aging time for LED2.

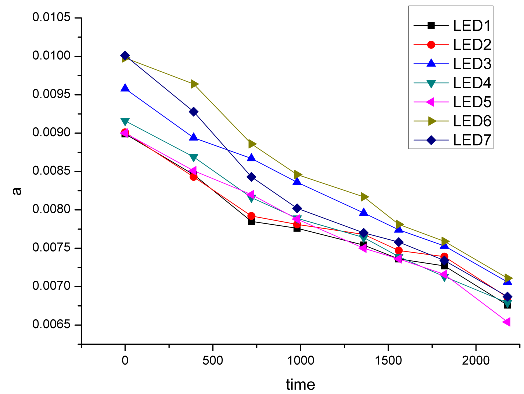

FIGURE 4. Variations of fitting parameter *a* for samples.

the sample LED2 at different points of the accelerated aging time.

The absolute values of the linear fitting parameter of *a* for all samples decline with the aging time increasing. The largest decline of this parameter occurs in sample LED7. The absolute value of the parameter is $10.01\times10\text{-}3(1/^{\circ}C)$ at the initial stage, and it is $6.87\times10\text{-}3(1/^{\circ}C)$ at the end. The relative decrement of the parameter is 31%. The smallest decline of the parameter occurs in sample LED2. The absolute value of the parameter is $9.01\times10\text{-}3(1/^{\circ}C)$ at the initial stage, and it is $6.86\times10\text{-}3(1/^{\circ}C)$ at the end. The relative decrement of the parameter is 24%. The data indicates that the variation of W/B ratio as Tj trends to be milder and milder in the aging process. Fig.4 shows the variations of the fitting parameter of *a* for all LED samples in the aging process.

C. VARIATION OF Tj IN AGING PROCESS

The chromaticity parameters of LED samples working in stable state under ambient temperature of 25°C are acquired at eight typical points of aging time, and then the correspondent W/B values are obtained. The Tj values at eight points of aging time for LED samples are also obtained, and listed in table 4. It can be seen that as aging time increasing, the junction temperature increases monotonically for all the samples. The largest increment of junction temperature during the aging test occurs on LED2 which is 11.1°C. The smallest increment of junction temperature occurs on LED1 which is 9.5°C. The junction temperatures of the seven samples are in a range from 61.6°C to 63.3°C at the initial stage, and from 71.7°C to 73.2°C at the end. Figure 5 shows the variation trends of the junction temperature within the aging time for all samples.

TABLE 4. Variation of Tj at ambient temperature of 25°C (unite: °C).

Aging time	LED1	LED2	LED3	LED4	LED5	LED6	LED7
0	63.3	61.8	61.7	61.9	61.6	62.4	62.1
360	65.9	64.5	63.8	63.8	64.8	65.3	65.1
720	67.9	67.2	66.1	66.6	66.9	67.1	66.8
980	68.4	69.1	67.7	68.0	67.5	68.8	68.1
1320	69.2	69.6	68.8	69.4	68.7	69.2	69.1
1560	70.1	70.4	69.5	70.6	69.8	70.1	70.1
1820	71	72.1	70.7	71.5	71.6	71.3	71.2
2180	72.8	73.2	71.7	72.3	72.3	72.2	72.3

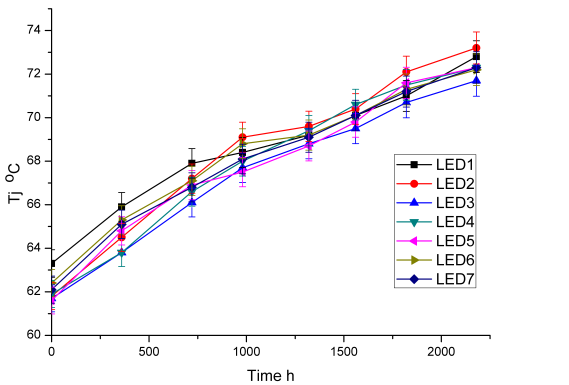

FIGURE 5. Variations of Tj at ambient temperature of 25°C for samples.

D. THE DECAY RATE OF β AND ACCELERATED LIFETIME ESTIMATE

The luminous fluxes of seven LED samples during the step-stress accelerated aging test are acquired at eight typical points of aging time. Table 5 lists the measurement values of luminous fluxes of Φ_t at the eight points of aging time for the samples. Fig.6 (a) shows the variation trends of the luminous fluxes of the samples within the aging time.

The vertical line at 980 hours of aging time in the figure represents the end of the first step and the beginning of the second step of the aging test. It is shown that the luminous fluxes of the seven samples are from 483.83 to 487.67 lumen initially, and from 432.85 to 455.86 lumen by the end of the first step of the aging. By the end of the total aging test, the luminous fluxes are from 393.00 to 421.44 lumen.

To eliminate the effect of the increase of junction temperature of samples on the luminous flux during the accelerated aging test, the values of the luminous fluxes of Φ_t given in table 5 should be modified according to (9) in section 2. According to the values of μ given in table 2 and the values of junction temperature given in table 4, the decrements of luminous fluxes of $\Delta\Phi_t$ are obtained and listed in table 5. It is shown that in the accelerated aging test, the decrements of luminous fluxes of $\Delta\Phi_t$ for the samples are in a range from 8.02 to 10.07 lumen by the end of the first step of the aging, and from 17.83 to 22.40 lumen by the end of the second step of the aging. With the data of $\Delta\Phi_t$ the luminous flux values of Φ_t are modified and shown in fig.6 (b), where the corrected luminous fluxes of the seven samples are from 441.82 to 457.90 lumen by the end of the first step of the aging. In a comparison, the unmodified values are from 432.85 to 455.86 lumen. By the end of the second step of the aging, the corrected luminous fluxes are from 412.74 to 441.30 lumen, and the unmodified values are from 393.00 to 421.44 lumen. That means the lumen maintenance getting higher by the modification.

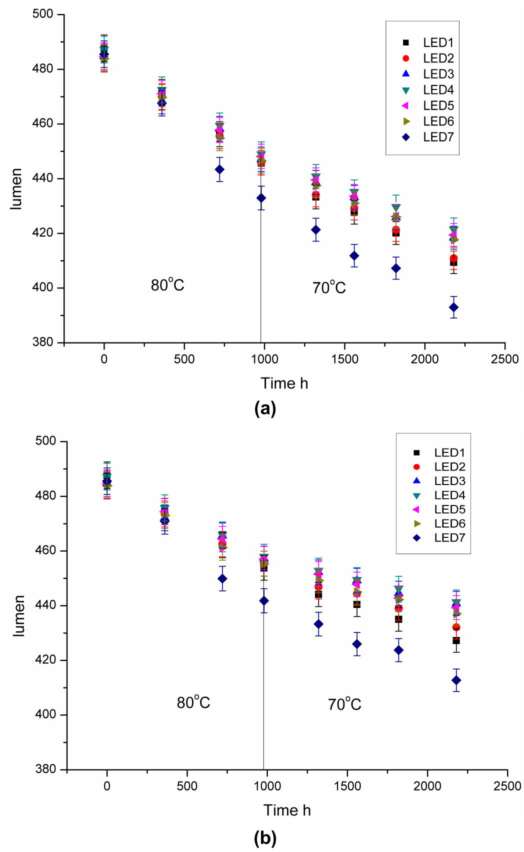

FIGURE 6. Luminous fluxes of seven samples at different points of aging time. (a) Before correction. (b) After correction.

According to the data of Φ_t in the first step the luminous maintenance rates of Φ_t/Φ_0 are acquired, which are then fitted by the exponential decay law. Fig.7 (a) shows the fitting results. Then β_{80} can be acquired and listed in table 6. The correspondent accelerated lifetimes of τ_{80} are then obtained and listed in table 6. Similarly, according to the corrected luminous fluxes of $\Phi_t + \Delta\Phi_t$ the luminous maintenance rates of $(\Phi_t + \Delta\Phi_t)/\Phi_0$ are acquired, which are then fitted by the exponential decay law. Fig.7 (b) shows the fitting results. According to the fittings the decay rates of β'_{80} and the accelerated lifetimes of τ'_{80} of the samples are obtained and listed in table 6. The dotted lines in Fig.7 show the rang of lumen maintenance at the end of the first step of the aging which is from 89.17% to 92.47% in (a) contracting to 91.00% to 94.32% in (b).

It can be seen from table 6 that β'_{80} is smaller than β_{80} for all the samples. Correspondingly, the accelerated lifetime of τ'_{80} is longer than that of τ_{80}. The accelerated lifetimes of

TABLE 5. Φt **and** $\Delta\ \Phi t$ **at aging points(lumen).**

	time	0hr	360 hr	720 hr	980 hr	1320 hr	1560 hr	1820 hr	2180 hr
LED1	Φ_t	487.67	471.56	456.28	455.86	433.31	427.67	420.14	409.39
	$\Delta\Phi_t$	0	2.94	5.89	8.02	10.80	12.76	14.89	17.83
LED2	Φ_t	484.13	470.03	455.55	445.85	434.07	429.24	421.31	410.88
	$\Delta\Phi_t$	0	3.50	7.01	9.54	12.85	15.19	17.72	21.23
LED3	Φ_t	484.73	468.43	458.23	447.12	438.65	443.17	425.82	418.42
	$\Delta\Phi_t$	0	3.70	7.40	10.07	13.56	16.03	18.70	22.40
LED4	Φ_t	487.17	472.50	459.43	448.97	440.82	435.21	429.70	421.44
	$\Delta\Phi_t$	0	3.28	6.56	8.93	12.03	14.21	16.58	19.86
LED5	Φ_t	484.62	471.10	457.80	448.14	439.57	433.58	426.16	417.40
	$\Delta\Phi_t$	0	3.29	6.57	8.95	12.05	14.24	16.62	19.90
LED6	Φ_t	483.83	469.74	454.81	446.60	437.43	431.05	425.97	417.64
	$\Delta\Phi_t$	0	3.21	6.43	8.75	11.78	13.93	16.25	19.46
LED7	Φ_t	485.51	467.64	443.39	432.95	421.34	411.85	407.27	393.00
	$\Delta\Phi_t$	0	3.26	6.52	8.87	11.95	14.12	16.48	19.74

TABLE 6. **Decay rate** β **and accelerated lifetime of first step of aging.**

	β_{70} (10^{-4})	β'_{70} (10^{-4})	β_{70}-β'_{70} (10^{-4})	T_{70} (hr)	τ'_{70} (hr)	$(\tau'_{70}-\tau_{70})/\tau'_{70}$
LED1	1.071	0.902	0.169	3330	3954	18.7%
LED2	1.204	1.070	0.134	2962	3333	12.5%
LED3	1.584	1.328	0.256	2252	2686	19.2%
LED4	1.437	1.228	0.209	2482	2904	17.0%
LED5	1.044	0.878	0.166	3417	4062	18.9%
LED6	1.134	0.982	0.152	3145	3632	15.4%
LED7	1.958	1.628	0.330	1821	2191	20.3%

τ'_{80} range from 1520 hours to 2997 hours, while that of τ_{80} range from 1329 hours to 2527 hours. The estimation errors of τ_{80} which are acquired by traditional method, are 15.6%, 12.8%, 14.3%, 16.4%, 18.6%, 15.8% and 14.9% for the seven samples, respectively.

For the second step of the accelerated aging test the luminous maintenance rate conforms to (7). According to the decay rates of the samples of β_{80} and the aging time of 980 hours in the first step, the values of $\beta_1 t_1$ in (7) for the samples are obtained. According to the data of Φ_t in the second step, the luminous maintenance rates of Φ_t/Φ_0 are acquired. Then the luminous maintenance rates are fitted by the exponential decay law of (7). Fig.8 (a) shows the fitting results for the samples. According to the fittings the decay rates of the samples under aging temperature of 70°C, β_{70}, and the correspondent accelerated lifetimes of τ_{70} are obtained and listed in table 7.

For the fittings of the corrected luminous maintenance in the second step of the accelerated aging test, the corrected decay rates of β'_{80} and the aging time of 980 hours in the first step are used to obtain the values of $\beta_1 t_1$ in (7). According to the corrected luminous fluxes of $\Phi_t + \Delta\Phi_t$ in the second step, the corrected luminous maintenance rates of $(\Phi_t + \Delta\Phi_t)/\Phi_0$ are acquired. Then the luminous maintenance rates are fitted by the exponential decay law of (7). Fig.8 (b) shows the fitting results. According to the fittings the decay rates of β'_{70} and the accelerated lifetimes of τ'_{70} are obtained and listed in table 7. The dotted lines in Fig.8 show the rang of lumen maintenance at the end of the second step of the aging which is from 80.95% to 86.54% in (a) and is from 85.01% to 90.65% in (b).

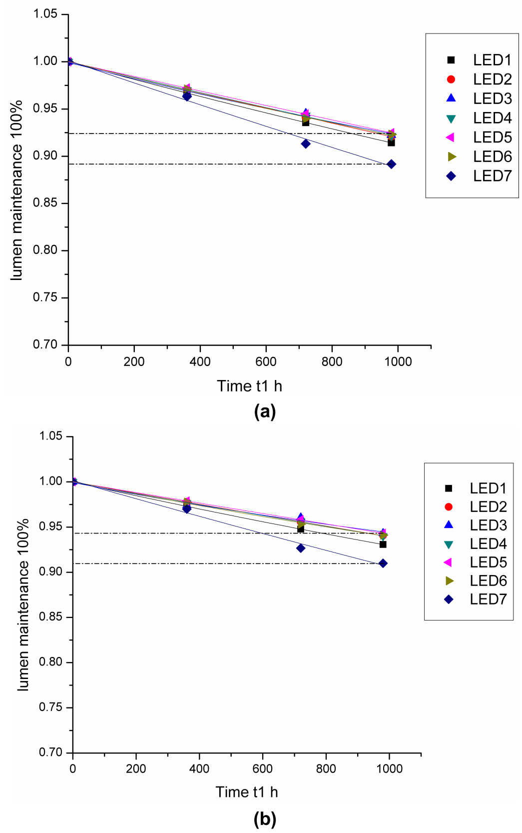

FIGURE 7. **Luminous flux maintenance rates as time for samples at ambient temperature of 80°C. (a) Before correction. (b) After correction.**

It can be seen from table 7 that β'_{70} is smaller than β_{70} for all samples. Correspondingly, the accelerated lifetime of τ'_{70} is longer than that of τ_{70}.The accelerated lifetimes of τ'_{70} range from 2191 hours to 4062 hours, while that of τ_{70} range from 1831 hours to 3417 hours. The estimation errors of τ_{70} are

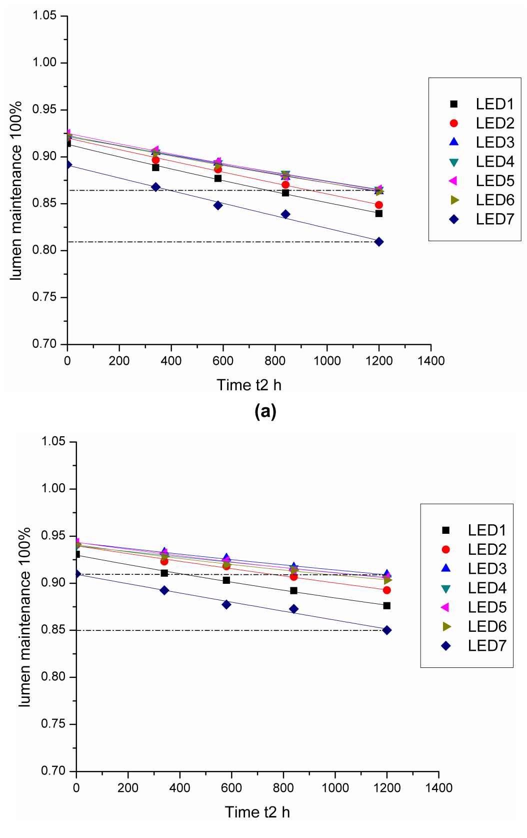

FIGURE 8. Luminous flux maintenance rates as time for samples at ambient temperature of 70°C. (a) Before correction. (b) After correction.

TABLE 7. Decay rate β and accelerated lifetime of second step of aging.

	β_{70} (10^{-4})	β'_{70} (10^{-4})	β_{70}-β'_{70} (10^{-4})	T_{70} (hr)	τ'_{70} (hr)	$(\tau'_{70}-\tau_{70})/\tau'_{70}$
LED1	1.071	0.902	0.169	3330	3954	18.7%
LED2	1.204	1.070	0.134	2962	3333	12.5%
LED3	1.584	1.328	0.256	2252	2686	19.2%
LED4	1.437	1.228	0.209	2482	2904	17.0%
LED5	1.044	0.878	0.166	3417	4062	18.9%
LED6	1.134	0.982	0.152	3145	3632	15.4%
LED7	1.958	1.628	0.330	1821	2191	20.3%

18.7%, 12.5%, 19.2%, 17.0%, 18.9%, 15.4% and 20.3% for the seven samples, respectively.

V. CONCLUSIONS

In this research, seven samples of white LED lamps are selected for the step-stress accelerated aging test under the temperature stresses of 80°C with aging time of 980 hours and 70°C with aging time of 1200 hours. The luminous fluxes are measured under ambient temperature of 25°C. The results show that the variation of W/B ratio as Tj satisfies a good linear relationship at all measurement points of aging time, with the R-square values greater than 0.98 in most cases. And the Tj increases monotonically during the aging time. For the seven samples, the range of junction temperatures under ambient temperature of 25°C is from 61.6°C to 63.3°C at the initial stage, and from 71.7°C to 73.2°C by the end of the aging. The increments of junction temperatures range from 9.5°C to 11.4°C.

The decrements of the luminous fluxes relevant to the Tj variations are obtained which are then used to modify the measurement values of luminous fluxes. With the modified luminous fluxes during the step-stress accelerated aging test the decay rates and the accelerated lifetimes in the first and second step of the aging are obtained and compared with that obtained by traditional method. The results show that the estimation errors of the accelerated lifetimes by traditional method are in a range from 12.8% to 18.6% in the first step of the aging and from 12.5% to 20.3% in the second step of the aging in this research.

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