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Original research article

Step-down accelerated aging test for LED lamps based on nelson models

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A B S T R A C T

In order to quickly acquire the lifetime and reliability prediction for LED lighting products, the method of step-down accelerated aging test based on Nelson models is experimentally studied in this paper. Ten Lide lamps and ten Philips lamps are used in the accelerated aging tests, with humidity less than 50%. The ambient temperatures are 90 °C and 70 °C for Lide lamps, and are 90 °C and 80 °C for Philips lamps. The models, the equal cumulative amount of degradation and the equal cumulative failure probability, are used to obtain the equivalent test time from one stress to another. The maximum likelihood function method is used to obtain two unknown parameters of Weibull distribution at the accelerated ambient temperatures. Then the distribution of the failure probability of LED lamp at ambient temperature of 25 °C is obtained by Arrhenius model. The lifetime tests recommended by Energy Star standard are conducted to verify the accuracy of the models. It is shown that the model of equal cumulative amount of degradation is with a smaller error of lifetime estimation which is respectively 1.74%, 2.41% and 6.57% at the failure probability of 63.2%, 10% and 1% for Lide lamps, and is respectively 8.19%, 1.06% and 5.89% for Philips lamps in this research. The total accelerated aging time about 1000 h is achieved in this experiment, which is quite satisfactory for a quick lifetime prediction of LED lamps recently.

1. Introduction

LED products are the new fourth generation energy source and are widely used in various lighting fields [1,2]. While its advantages in energy conservation and environmental protection have been well known, its long lifetime and good reliability are still being questioned. Currently the aging test of LED lamps uses the criteria of IES LM-79 as the reference [3], and the test time is recommended to be 6000 h at least. As a consequence, quick and accurate prediction of lifetime and reliability for LED products becomes a new research focus [4–7].

Constant stress accelerated aging test is more mature for LED lighting products [8–12] where for purely thermal stress, at least two tests have to be done respectively under different stresses to obtain the activation energy. There are two disadvantages with this method. The inconsistency of two groups of samples may lead to certain error, and the total time of two accelerated aging tests is long as using one set of equipment. In a comparison, step-stress accelerated test is a continuous test which is with relatively shortened test time. The models include equal cumulative amount of degradation (model 1) and equal cumulative failure probability (model 2). The first model means that they have equal cumulative amount of degradation

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for some time under different thermal stress. The second model means that they have equal cumulative failure probability for some time under different thermal stress. Y. T. Hong [13] et al. reported the aging test of LED light source modules under thermal stresses based on model 1. M. Cheng [14] and H. H. Cheng [15] et al. reported optimization method of maximum likelihood function based on model 1. J. Hao [16] et al. reported the design of two-step-down aging test for LED lamps based on model 1. W. H. Chen [17] et al. reported aging method of the electrical connector under thermal stresses based on model 2. J.P. Zhang [18] et al. reported the aging method of OLED under current stresses based on model 2. However, to the best of our knowledge, there has been no report about which of the models is more suitable for the data processing in step-down accelerated aging test of LED lamps, yet.

In this paper, with the Weibull distribution [19,20] of the failure probability and under thermal stresses, step-down accelerated aging tests of two types of LED lamps are conducted, and the data is processed by two models, in a comparison manner. Then, the lifetimes of LED lamps are obtained by use of the Arrhenius model. The accelerated aging test time about 1000 h is achieved. It is shown that model 1 is more suitable for step-down aging test of LED lamps.

2. Theory

2.1. Arrhenius model and weibull distribution

According to the standard of IES TM-28 [21], the lumen maintenance of LED products meets the exponential decay law:

$$\Phi_j = \exp\left(-\beta_{T_j} t_j\right) \tag{1}$$

Where Φ_j is the lumen maintenance under j-th (j = 1, 2. . .k) thermal stress, β_{T_j} is the decay rate at junction temperature of T_j and t_j is the test time. The change of β_{T_j} over T_j satisfies Arrhenius model:

$$\beta_{T_j} = A\exp(-E_a/kT_j) \tag{2}$$

Where A is a constant, E_a represents the activation energy and k is Boltzmann's constant. The test time is considered to be the lifetime of LED lamp when Φ_j equals to 0.7 [21]:

$$\tau_j = -\frac{\ln(0.7)}{\beta_{T_j}} \tag{3}$$

The failure probability of LED lamp with respect to the lifetime is consistent with Weibull distribution:

$$F(\tau_j) = 1 - e^{-\left(\frac{\tau_j}{\eta_j}\right)^{m_j}} \tag{4}$$

Where $F(\tau_j)$ is the failure probability, m_j represents the so-called shape parameter and η_j represents the characteristic lifetime. By differentiating Eq. (4), we have the density function of failure probability as:

$$f(\tau_j) = \frac{m_j}{\eta_j}\left(\frac{\tau_j}{\eta_j}\right)^{m_j-1}\exp\left[-\left(\frac{\tau_j}{\eta_j}\right)^{m_j}\right] \tag{5}$$

Then the maximum likelihood function method is adopted to solve the unknown parameters of η_j and m_j at junction temperature of T_j. The correspondent logarithm of likelihood function of Eq. (5) for i-th sample can be written as:

$$I_i = \ln\left(\frac{m_j}{\eta_j}\left(\frac{\tau_j i \eta_j}{}\right) m_j - 1 \exp\left[-\left(\frac{\tau_j i \eta_j}{}\right) m_j\right]\right) \tag{6}$$

For the sample size of n, the function can be expressed as:

$$I = \sum_{i=1}^{n} I_i = \sum_{i=1}^{n} \ln f(\tau_j i) = \sum_{i=1}^{n} \ln\left(\frac{m_j}{\eta_j}\left(\frac{\tau_j i \eta_j}{}\right) m_j - 1 \exp\left[-\left(\frac{\tau_j i \eta_j}{}\right) m_j\right]\right) \tag{7}$$

The following equation can be then solved and the unknown parameters of Weibull distribution are obtained.

$$\begin{cases} \dfrac{\partial I}{\partial m_j} = 0 \\ \dfrac{\partial I}{\partial \eta_j} = 0 \end{cases} \tag{8}$$

The procedure from Eqs. (5) to (8) is actually executed by the command of "wblfit" in MATLAB Statistics Toolbox. In MATLAB software, the values of lifetimes of samples acquired by the exponential fitting of lumen maintenance under j-th thermal stress for each sample are inputted firstly, and then the command of "wblfit" is sent to get the unknown parameters of Weibull distribution.

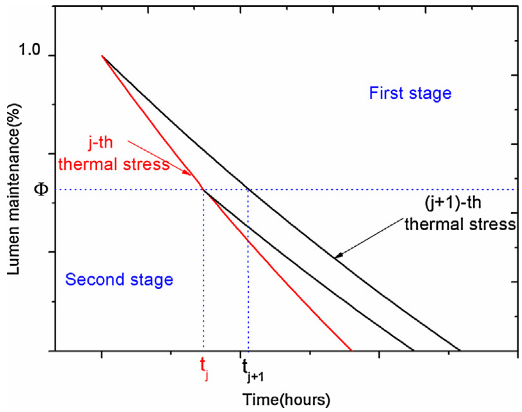

Fig. 1. The step-down accelerated aging test of model 1.

2.2. The analysis of models

According to the cumulative failure model proposed by Nelson, the residual lifetime of product depends only on the current failed part and current stress, and it has nothing to do with accumulation way. The following Nelson models, model 1 and model 2, can be adopted to obtain the equivalent test time of step-down aging test under thermal stresses for LED lamps.

2.2.1. Model 1

Fig. 1 shows the procedure of step-down accelerated aging test of model 1, where the abscissa represents the aging time and the ordinate represents the lumen maintenance. The aging stage is as the first stage when the lumen maintenance is greater than or equals to Φ, and it is as the second stage when the lumen maintenance is less than Φ. The decay curve of the lumen maintenance consists of the red line from j-th thermal stress at the first stage and the black line from the (j + 1)-th thermal stress at the second stage. The ending time under j-th thermal stress is the starting time under (j + 1)-th thermal stress. The cumulative amount of degradation with the test time of t_j under j-th thermal stress is considered to be equal to that with the test time of t_{j+1} under (j + 1)-th thermal stress for LED lighting products. That is:

$$\Phi_{j+1}(t_{j+1}) = \Phi_j(t_j) \tag{9}$$

Where t_{j+1} is the equivalent test time from j-th to (j + 1)-th thermal stress, and $\frac{t_{j+1}}{t_j}$ is the acceleration factor. Combining Eq. (1) and (9), we have:

$$t_{j+1} = \beta_{T_j} \frac{t_j}{\beta_{T_{j+1}}} \tag{10}$$

The total test time of t_{j+1_total} under (j + 1)-th thermal stress, defined as the sum of above equivalent test time and the test time at second stage, can be written as:

$$t_{j+1\_total} = t_{j+1}{}' + t_{j+1} \tag{11}$$

Where t_{j+1}' represents the test time at second stage. Substituting Eq. (11) into Eq. (1), we have lumen maintenance under (j + 1)-th thermal stress:

$$\Phi_{j+1} = \exp\left(-\beta_{T_{j+1}} t_{j+1\_total}\right) \tag{12}$$

With Eq. (3), the accelerated lifetime of LED lamp can be obtained under (j + 1)-th thermal stress:

$$\tau_{j+1} = -\frac{\ln(0.7)}{\beta_{T_{j+1}}} \tag{13}$$

According to Eqs. of (10), (12) and (13), we have a new expression of the lifetime which can be transformed into a linear equation. Assuming the sample size of n, with exponential fitting for lumen maintenances of each sample we can get n decay rates and n accelerated lifetimes. Then with the same procedure described in Eqs. of (4)–(8), the characteristic lifetime and shape parameter of Weibull distribution at junction temperature of T_{j+1} are obtained.

2.2.2. Model 2

Fig. 2 shows the procedure of step-down accelerated aging test of model 2, where the abscissa represents aging time, and the ordinate represents failure probability. The aging stage is as the first stage when failure probability is less than or equals

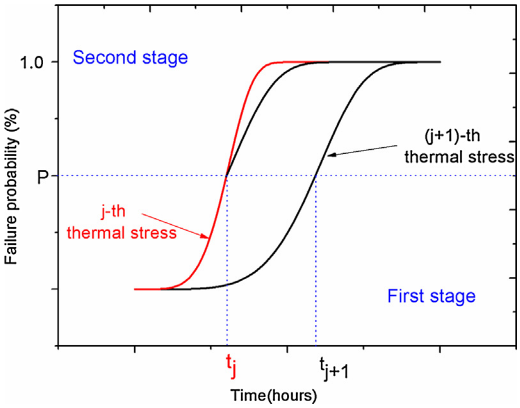

Fig. 2. The step-down accelerated aging test of model 2.

to P, and it is as the second stage when failure probability is greater than P. The decay curve of step-down aging consists of the red line from j-th thermal stress at the first stage and the black line from (j + 1)-th thermal stress at the second stage. The ending time under j-th thermal stress is the starting time under (j + 1)-th thermal stress. The cumulative failure probability with the test time of t_j under j-th thermal stress is considered to be equal to that with the test time of t_{j+1} under (j + 1)-th thermal stress for LED lighting products. That is:

$$F_{j+1}(t_{j+1}) = F_j(t_j) \tag{14}$$

Combining Eq. (4) and (14), we have:

$$t_{j+1} = \eta_{j+1}\left(\frac{t_j}{\eta_j}\right)^{\frac{m_j}{m_{j+1}}} \tag{15}$$

Combining Eq. (15) with Eqs. of (11)–(13), the lifetime of τ_{j+1} with unknown parameters of η_{j+1} and m_{j+1} can be obtained. The relationship between accelerated lifetime and failure probability is then given by:

$$F(\tau_{j+1}) = 1 - e^{-\left(\frac{\tau_{j+1}}{\eta_{j+1}}\right)^{m_{j+1}}} \tag{16}$$

Then the maximum likelihood function is established to solve the unknown parameters. For the sample size of n, the likelihood function under (j + 1)-th thermal stress is given by:

$$I = \sum_{i=1}^{n} I_i = \sum_{i=1}^{n} \ln f(\tau_{(j+1)}i) = \sum_{i=1}^{n} \ln\left(\frac{m_{j+1}}{\eta_{j+1}}\left(\frac{\tau_{(j+1)}i\eta_{j+1}}{}\right)m_{j+1} - 1\ \exp\left[-\left(\frac{\tau_{(j+1)}i\eta_{j+1}}{}\right) m_{j+1}\right]\right) \tag{17}$$

Suppose $\alpha_{(j+1)i} = \ln(\tau_{(j+1)i})$, $\kappa_{j+1} = \ln(\eta_{j+1})$ and $\gamma_{j+1} = \frac{1}{m_{j+1}}$, Eq. (17) can be rewritten as:

$$I = \sum_{i=1}^{n}(-\ln\gamma_{j+1} - \alpha_{(j+1)i} + (\alpha_{(j+1)i} - \kappa_{j+1})/\gamma_{j+1} - \exp((\alpha_{(j+1)i} - \kappa_{j+1})/\gamma_{j+1})) \tag{18}$$

We assume m_{j+1} equal to m_j firstly. Using the maximum likelihood function, the initial characteristic lifetime of Weibull distribution of η_{j+1} is obtained. With the initial parameter values, the following equation can be solved by iterative procedure, and the accurate solutions of shape parameter and characteristic lifetime can be obtained.

$$\begin{cases} \dfrac{\partial I}{\partial \kappa_{j+1}} = 0 \\ \dfrac{\partial I}{\partial \gamma_{j+1}} = 0 \end{cases} \tag{19}$$

2.3. Derivation of lifetime at room temperature

With characteristic lifetimes under two thermal stresses, the activation energy can be obtained according to Eq. (2):

$$E_a = \frac{k\ln\left(\eta_j/\eta_{j+1}\right) 1/T_j - 1/T_{j+1}}{} \tag{20}$$

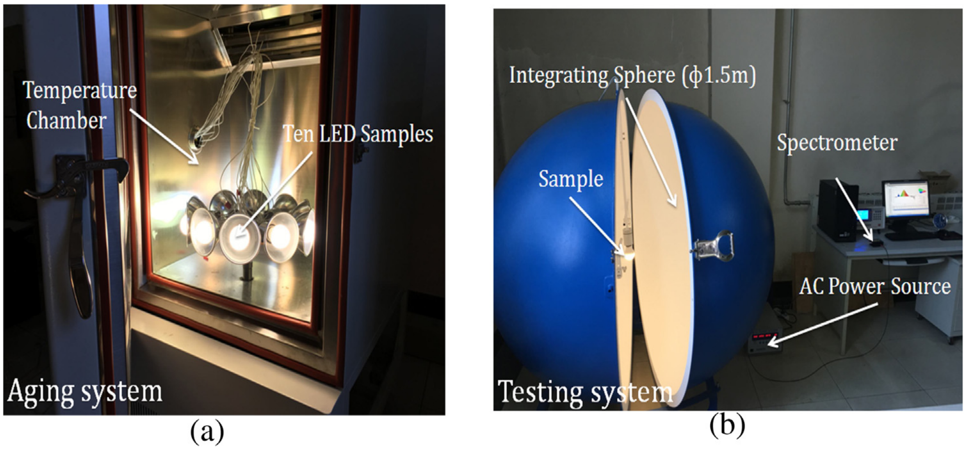

Fig. 3. Test set-ups of step-down accelerated test. (a) aging system, (b) testing system.

Whereη_j andη_{j+1} are the characteristic lifetimes under j-th and (j + 1)-th thermal stresses, respectively. The characteristic lifetime of LED product at ambient temperature of 25 °C is then calculated by:

$$\eta_{0j} = \eta_{T_j} \exp\left[\frac{E_a}{k}\left(\frac{1}{T_{0j}} - \frac{1}{T_j}\right)\right] \tag{21}$$

Where η_{0j} is the characteristic lifetime at ambient temperature of 25 °C,η_{T_j} is the accelerated characteristic lifetime, T_j is the junction temperature under accelerated condition and T_{0j} is the junction temperature under the ambient temperature of 25 °C.

3. Experiments and data analysis

3.1. Experiments

Fig. 3 are the test set-ups of step-down accelerated test. As shown in Fig. 3(a), the aging system consists of a temperature chamber and LED samples. The error bands on the temperature chamber is ±1 °C.The testing system consists of an AC power source, an integrating sphere, a spectrometer from LanFei company and a computer. The chamber temperature of 90 °C and 70 °C are selected for the step-down accelerated aging test. Samples are encapsulated by Lide company with the same components including chips from ES company, YAG phosphor, 6630 potting glue, DX20C patch glue, and driver from Lide company. The correlated color temperatures of these samples are about 3500–3580 K. The number of samples is ten. Before the accelerated aging tests, samples have experienced environmental tests of vibration, shock and current. In this way defects in drivers, such as bad soldering joints and defective electronic components, are excluded. The samples also have experienced high-low temperature test in a period of time to exclude instability state of the samples.

The ambient temperature is selected as 90 °C and 70 °C. The experiment is done according to reference [23], and the result shown that the highest temperature is about 100 °C. Therefore, a safety temperature is chosze as 90 °C. The junction temperatures of the LED samples are actually measured by means of spectral analysis [24], which are 332.15 K, 372.15 K and 391.15 K at ambient temperature of 298.15 K(25 °C), 343.15 K (70 °C) and 363.15 K (90 °C), respectively. Before each data acquisition, lamps are cooled from high temperature to stable 25 °C at least two hours. The accelerated aging time is respectively 424 h and 462 h at ambient temperature of 90 °C and 70 °C. The acquired data of lumen maintenance is shown in Fig. 4. Where the ordinate is the percentage of lumen maintenance and the abscissa is the accelerated test time.

3.2. The data analysis of step-down stress test

The lumen maintenance date at the first stage of the aging test in Fig. 4 is fitted according to Eq. (1):

$$\Phi = \exp(-\beta_{90} t_{90}) \tag{22}$$

Where β_{90} represents the decay rate at ambient temperature of 90 °C. The fitted curves of ten samples are shown on the left of Fig. 5 and the correspondent values of β_{90} are listed in the second column of Table 1. The accelerated lifetime can be then obtained by:

$$\tau_{90} = -\frac{\ln(0.7)}{\beta_{90}} \tag{23}$$

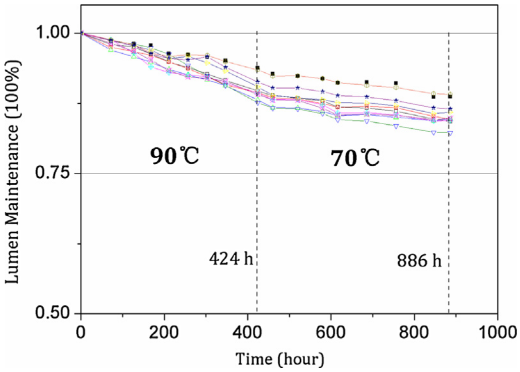

Fig. 4. The variation of lumen maintenance over time based on the acquired data.

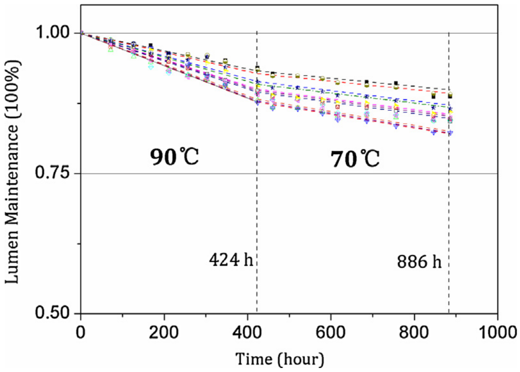

Fig. 5. The fitted curves of lumen maintenance over time.

The calculated accelerated lifetimes of τ_{90} are listed in third column of Table 1. With the data of lifetimes, the characteristic lifetime and the shape parameter of Weibull distribution are obtained by the maximum likelihood function method, which are respectively 1696 h and 4.7.

3.2.1. Data processing with model 1

Substituting β_{90} and the aging time of 424 h at the first stage into Eq. (10), we have the equivalent test time as a function of β_{70} for ten samples:

$$t_{equi} = 424\frac{\beta_{90}}{\beta_{70}} \tag{24}$$

According to Eqs. of (11), (12) and (24), the lumen maintenance date at the second stage of the aging test in Fig. 4 can be fitted by the exponential equation given by:

$$\Phi = \exp(-424\beta_{90})\exp(-\beta_{70}t_{70}) \tag{25}$$

Table 1
The decay rates and lifetimes at ambient temperature of 90 °C and 70 °C.

	Temperature			
	90 °C		70 °C	
No.	β_{90}	τ_{90} (h)	β_{70}	τ_{70} (h)
1	0.0003051	1169	0.0001481	2408
2	0.0002992	1192	0.0001456	2450
3	0.0002625	1359	0.0001182	3018
4	0.0002533	1408	0.0001158	3079
5	0.0002522	1414	0.0001121	3182
6	0.0002505	1424	0.0001087	3281
7	0.0002222	1605	0.0001045	3413
8	0.0002140	1667	0.0001036	3442
9	0.0001756	2031	0.0000828	4310
10	0.0001623	2197	0.0000797	4477

Table 2
The calculated data of unknown parameters.

	Parameters	Model 1	Model 2
70 °C	Characteristic lifetime	3575 h	3482 h
	Shape parameter	5.4	6.04

Table 3
Calculated parameter values under the two modes.

Temperature	Model 1		Model 2	
Activation energy	0.492 eV		0.475 eV	
Parameter	characteristic lifetime	shape parameter	characteristic lifetime	shape parameter
Parameter value	22,686 h	5.4	20,726 h	6.04

The fitted curves of ten samples are shown on the right of Fig. 5 and the correspondent values of β_{70} are listed in the fourth column of Table 1. The accelerated lifetime of τ_{70} can be then obtained by:

$$\tau_{70} = -\frac{\ln(0.7)}{\beta_{70}} \tag{26}$$

The calculated accelerated lifetimes of τ_{70} are listed in fifth column of Table 1. With the data of lifetimes, the characteristic lifetime and the shape parameter of Weibull distribution are obtained by the maximum likelihood function method, which are respectively 3575 h and 5.4. The results are listed in third column of Table 2.

3.2.2. Data processing with model 2

Substituting the aging time of 424 h at the first stage, and the solved characteristic lifetime of 1696 h and the shape parameter of 4.7 at ambient temperature of 90 °C into Eq. (15), we have the equivalent test time as a function of m_{70} and η_{70}, which is expressed as:

$$t_{equi} = \eta_{70}\left(\frac{424}{1696}\right)^{\frac{4.7}{m_{70}}} \tag{27}$$

Substituting the equivalent test time given by Eq. (27) and the lumen maintenance of Φ_{462} at the end of the second stage of aging into Eq. (11), and using Eq. (12) and (13), we have the accelerated lifetime of LED lamp at ambient temperature of 70 °C given by:

$$\tau_{70} = \frac{\ln(0.7) \times \left(462 + \eta_{70}\left(\frac{424}{1696}\right)^{\frac{4.7}{m_{70}}}\right)}{\ln \Phi_{462}} \tag{28}$$

Substituting the lifetime given by Eq. (28) into Eq. (16), we have the Weibull distribution:

$$F(\tau_{70}) = 1 - e^{-\left(\frac{462\times\ln(0.7)}{\eta_{70}\ln\Phi_{462}} + \frac{\ln(0.7)\times\left(\frac{424}{1696}\right)^{\frac{4.7}{m_{70}}}}{\ln\Phi_{462}}\right)^{m_{70}}} \tag{29}$$

The likelihood function of ten samples at ambient temperature of 70 °C is established with Eqs. of (17) and (18), and the unknown parameters of m_{70} and $\eta_{70}$are then solved by means of iterative procedure with Eq. (19). The results are listed in fourth column of Table 2.

3.3. Calculation of lifetime at room temperature

Substituting the acquired characteristic lifetimes into Eq. (20), we have

$$E_a = \frac{k\ln\left(\eta_{90}/\eta_{70}\right)}{1/T_{90} - 1/T_{70}} \tag{30}$$

The calculated activation energies are respectively 0.492 eV and 0.475 eV with model 1 and 2, and are listed in second line of Table 3. It is noticed that the better way for inference on E_a is using a global maximum likelihood fit over temperature to give a lower standard error of E_a. In this research the estimation of E_a is based on the parameters acquired from only two thermal stresses, which causes a certain error in the estimation indeed. Then, the characteristic lifetime at ambient temperature of 25 °C is calculated by:

$$\eta_{25} = \eta_{70}\exp\left[\frac{E_a}{k}\left(\frac{1}{T_{25}} - \frac{1}{T_{70}}\right)\right] \tag{31}$$

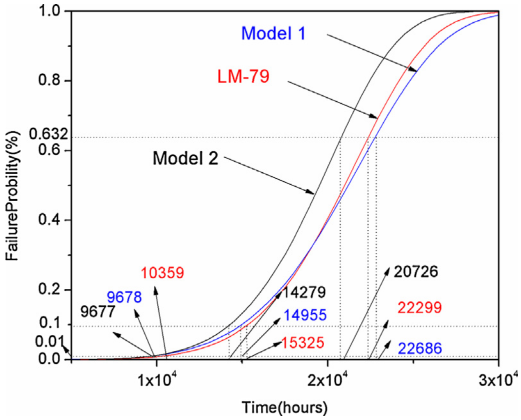

Fig. 6. Curves of Weibull distribution.

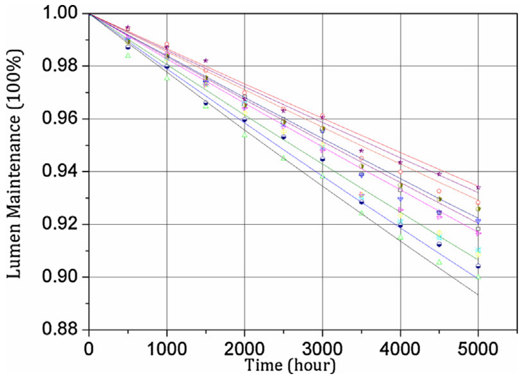

Fig. 7. The variation of lumen maintenance over time.

Table 4
The decay rates and lifetimes for LED lamps.

No.	1	2	3	4	5	6	7	8	9	10
Decay rate	2.26 e-05	2.15 e-05	2.12 e-05	1.96 e-05	1.73 e-05	1.66 e-05	1.55 e-05	1.47 e-05	1.41 e-05	1.35 e-05
Lifetime (h)	15,806	16,614	16,816	18,189	20,604	21,518	22032	24,282	25,361	26,359

The calculated characteristic lifetimes and shape parameters are listed in fourth line of Table 3. The correspondent Weibull distribution curves are shown in Fig. 6, where the blue curve is acquired by model 1 and the black curve is acquired by model 2. It can be seen that at the failure probability of 63.2%, 10% and 1%, the correspondent lifetime is respectively 22,686, 14,955 and 9678 h for model 1, and it is respectively 20,726, 14,279, and 9677 h for model 2.

3.4. Comparison with LM-84 combined with TM-21 standart test

To verify the accuracy of the test method, we implement the lifetime test of the same type of lamps based on Energy Star standards [21,22] which is 6000 h aging test at ambient temperature of 25 °C. According to the standard, data in the first 1000 h is excluded because of its relatively large fluctuations. But, the samples have excluded the instability state before accelerated aging test. Therefore the instability time cannot be equivalent to the time of accelerated aging. Taking into account the purpose of this paper is the error analysis of two methods. So, the first 1000 h only to be chosen deleted. Fig. 7 shows the variations of lumen maintenances of lamps over time. The lumen maintenances are then fitted by exponential function. The correspondent decay rates of β_{25} are listed in the second line of Table 4. According to Eq. (3), the lifetime of τ_{25} is then obtained by:

$$\tau_{25} = -\frac{\ln(0.7)}{\beta_{25}} \tag{32}$$

The calculated lifetimes are listed in the third row of Table 4.

With the data of lifetimes, the characteristic lifetime and shape parameter of Weibull distribution are obtained by the maximum likelihood function method. The correspondent Weibull distribution curve by LM-79 method is shown as the red

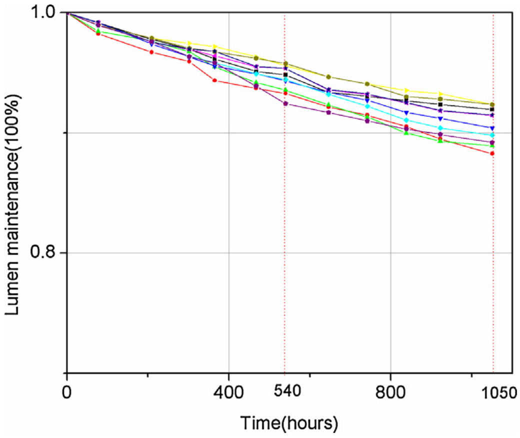

Fig. 8. The variation of lumen maintenance over time based on the acquired data.

curve in Fig. 6. It can be seen that the lifetime is 22,299, 15325 and 10359 h at the failure probability of 63.2%, 10% and 1%, respectively. These are compared with the lifetimes given in Section 3.3. It is shown that at the failure probability of 63.2%, 10% and 1%, the error of lifetime estimation is respectively 1.7%, 2.4% and 6.6% with model 1, and it is respectively 7.1%, 6.8% and 6.6% with model 2. Model 1 is more suitable for data processing of step-down accelerated aging test for Lide lamps.

3.5. Experiment and data analysis with Philips lamps

To further verify above conclusion, we repeat the experiment with LED lamps from Philips company. The correlated color temperatures of these samples are about 3000 K. The ambient highest temperature is selected as 90 °C. The experiment is also done according to reference [23], and the result shown that the highest temperature is about 105 °C. Considerating the junction temperatures, a safety temperature is chosze as 90 °C. The accelerated ambient temperature is 90 °C at first stage of the step-down aging test, and it is 80 °C at the second stage. The junction temperatures are measured to be 343.15 K, 389.15 K and 398.15 K at ambient temperature of 298.15 K(25 °C), 353.15 K (80 °C) and 363.15 K (90 °C), respectively. The accelerated aging time at the first stage is 540 h and it is 510 h at the second stage. The acquired data of lumen maintainences is shown in Fig. 8. Where the ordinate is the percentage of lumen maintenance and the abscissa is the accelerated test time.

The lumen maintainences at the first stage of the aging test in Fig. 8 are fitted according to Eq. (1), and the fitted curves of ten samples are shown on the left of Fig. 9. The decay rate and the accelerated lifetime for each sample are obtained from the fitting, and are listed in the second and third column of Table 5 respectively. The characteristic lifetime and shape parameter of Weibull distribution are then obtained, by means of maximum likelihood function, which are respectively 3242 h and 7.5.

Firstly, the model 1 is used to deduce the equivalent test time from the ambient temperature of 90 °C to 80 °C. The lumen maintainences at the second stage in Fig. 8 are fitted, and the fitted curves are shown on the right of Fig. 9. The decay rate and accelerated lifetime of each lamp are obtained, and are listed in the fourth and fifth column of Table 5 respectively. The unknown parameters of Weibull distribution are then obtained, by means of maximum likelihood function, and listed in the third column of Table 6.

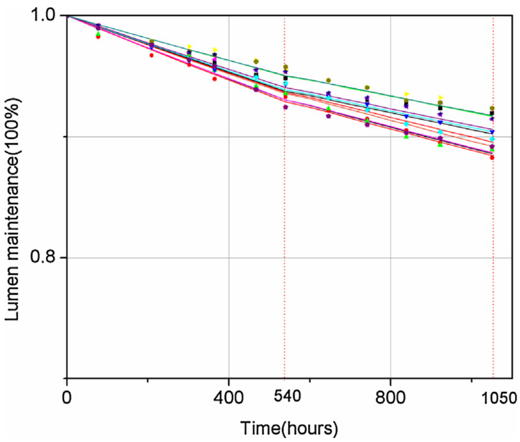

Fig. 9. The fitted curves of lumen maintenance over time.

Table 5
The values of decay rates and lifetimes for 90 °C and 80 °C stress.

No.	Temperature			
	90 °C		80 °C	
	β_{90}	τ_{90} (h)	β_{80}	τ_{80} (h)
1	0.0001367	2610	0.0000980	3641
2	0.0001338	2666	0.0000975	3657
3	0.0001333	2676	0.0000961	3710
4	0.0001229	2903	0.0000957	3726
5	0.0001209	2949	0.0000896	3982
6	0.0001191	2994	0.0000768	4647
7	0.0001170	3049	0.0000751	4751
8	0.0001134	3145	0.0000748	4771
9	0.0000943	3781	0.0000712	5011
10	0.0000940	3794	0.0000707	5048

Table 6
The calculated data of unknown parameters.

	Parameters	Model 1	Model 2
80 °C	Characteristic lifetime	4547 h	4399 h
	Shape parameter	8.8	9.2

Table 7
Calculated parameter values under the two modes.

Temperature	Model 1		Model 2	
Activation energy	0.502 eV		0.453 eV	
Parameter	characteristic lifetime	Shape parameter	characteristic lifetime	Shape parameter
Parameter value	33,827 h	8.8	26,904 h	9.2

Then the model 2 is used to deduce the equivalent test time from the ambient temperature of 90 °C to 80 °C. The accelerated lifetime and the Weibull distribution are then expressed as function of m_{80} and η_{80}. The maximum likelihood function method is used to solve the unknown parameters. The solved parameters are listed in fourth column of Table 6.

The activation energy is calculated with the characteristic lifetimes at the ambient temperatures of 90 °C and 80 °C. The results are listed in the second line of Table 7. Then, the characteristic lifetime at ambient temperature of 25 °C is calculated. The obtained characteristic lifetimes and shape parameters are listed in the fourth line of Table 7. The correspondent Weibull distribution curves are shown in Fig. 10, where the blue curve is with model 1 and the black curve is with model 2. It can be seen that at the failure probability of 63.2%, 10% and 1%, the correspondent lifetime is respectively 33,827, 26,194 and 20,055 h for model 1, and it is respectively 26,904, 21,066 and 16,318 h for model 2.

The lifetime test of the same type of lamps based on Energy Star standards is implemented. The variations of lumen maintainences of lamps over time are shown in Fig. 11. The lumen maintainences are then fitted by the exponential function. The decay rate and lifetime of each lamp are obtained, which are listed in Table 8. The characteristic lifetime and shape parameter of Weibull distribution are obtained, by means of maximum likelihood function. The correspondent Weibull

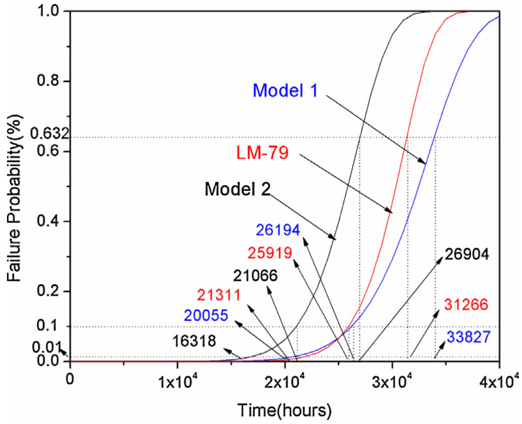

Fig. 10. Curves of Weibull distribution.

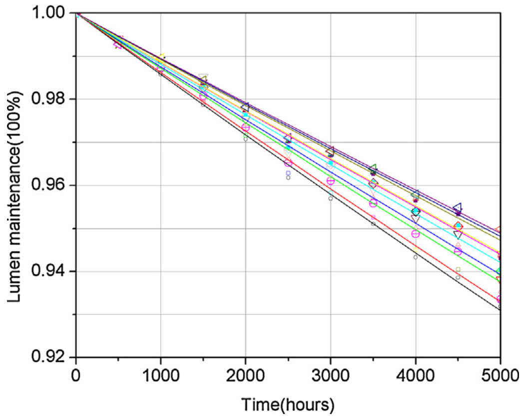

Fig. 11. The variation of lumen maintenance over time.

Table 8
The decay rates and lifetimes for LED lamps.

No.	1	2	3	4	5	6	7	8	9	10
Decay rate	1.43 e-05	1.39 e-05	1.29 e-05	1.25 e-05	1.19 e-05	1.15 e-05	1.14 e-05	1.08 e-05	1.06 e-05	1.05 e-05
Lifetime (h)	24,897	25,689	27,648	28,498	29,898	30,956	31,152	32,926	33,519	33,996

distribution curve is shown as the red curve in Fig. 10. It can be seen that the lifetime is 31,266, 25,919 and 21,311 h at the failure probability of 63.2%, 10% and 1%, respectively. It is shown that the error of lifetime estimation with model 1 is respectively 8.2%, 1.1% and 5.9%, and it is respectively 14.0%, 18.7% and 23.5% with model 2. For Philips lamps, model 1 is also more suitable for data processing of step-down accelerated aging test.

4. Conclusions

We have verified the step-down accelerated aging test under thermal stress for LED lamps by experiments. Two models are adopted in the data processing in a comparison manner. The selected ambient temperatures are 90 °C and 70 °C for Lide lamps, and are 90 °C and 80 °C for Philips lamps. The maximum likelihood function method is adopted in the calculation of parameters of Weibull distributions under accelerated stresses. The Weibull distribution at room temperature is then obtained by Arrhenius model. For Lide lamps the lifetime is respectively 22,686, 14,955 and 9678 h at the failure probability of 63.2%, 10% and 1% by model 1, and it is respectively 20,726, 14,279 and 9677 h by model 2. For Philips lamps it is respectively 33,827, 26,194 and 20,055 h by model 1, and it is respectively 26,904 h, 21,066 and 16,318 h by model 2. The lifetime test recommended by Energy Star standard is conducted to evaluate the effectiveness of the two models. The results indicate that model 1 is with a smaller error of lifetime estimation which is respectively 1.7%, 2.4% and 6.6% at above three failure probabilities for Lide lamps, and is respectively 8.2%, 1.1% and 5.9% for Philips lamps. Therefore model 1 is more suitable for data processing of step-down accelerated aging of LED lamps. The total accelerated aging time about 1000 h is achieved in this experiment, which is quite satisfactory for a quick lifetime prediction of LED lamps recently.

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