

A Novel Hybrid Method for Reliability Prediction of High-Power LED Luminaires

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Abstract

High power light-emitting diode (LED) has gained more and more applications because LED has many advantages over traditional light sources. However, it is extremely time-consuming and complicated to evaluate the LED luminaires reliability, in particular, the luminous degradation. In this work, a novel hybrid method, which combines the thermal modeling and temperature measurement, is proposed to estimate the junction temperature of high-power LEDs at system level, and therefore predict the lifetime of LED luminaries based on the known LM-80 data. First, a reference point at a luminaire system is selected to measure the temperature in the operating mode. Secondly, thermal modeling is performed to predict the reliable relationship between the junction temperature and the temperature of reference point (measuring point). Finally, the relationship between lifetime and junction temperature provided by the known LM-80 database is applied to estimate the LED luminaire's lifetime. To validate the predicted junction temperature, the thermal measuring experiments combined with the thermal tester T3ster are also implemented in this paper. It is found that, after a luminaire operates to a steady situation, the temperature difference between the reference point and the junction point reaches a constant, which indicates the thermal resistance between them can be simplified as a stable value. Therefore, the junction temperature of a luminaire can be obtained based on the temperature measurement of a measuring point and the thermal modeling. The lifetime predicted with the proposed method meets closely the lifetime estimated by vendor. The proposed method is expected to be very useful in future LED luminaire qualification test specification, instead of running lumen maintenance test to extrapolate the lifetime.

1. Introduction

High power light-emitting diode (LED) has gained more and more applications because LED has many advantages over traditional light sources, such as high luminous efficiency, energy saving, environment friendly, and long lifetime [1]. However, excessive junction temperature will cause reliability problems such as low quantum efficiency, wavelength shifts, short lifetime, and even catastrophic failure. In order to achieve the equivalency of the lifetime between LED light sources and LED luminaries, system level thermal design is one of the most critical factors. Proper thermal design at the package and luminaries level will keep

junction temperature in the desired range, and therefore the advantage of the longer lifetime can be realized.

The life-time assessment is becoming a big concern for the emerging illumination applications. According to the SSL Research and Development Manufacturing Roadmap from U.S department of energy at July 2011, a recommend expedited compliance testing and certification would be proposed until the end of 2013 and the beginning of 2014 [2]. Currently, it is extremely time-consuming and complicated to evaluate the LED luminaires reliability, in particular, the luminous depreciation. Energy Star program requires at least 6000 hours luminous test at product level. It is requested urgently to develop an effective and fast life-time qualification method to support and drive LED industry. Some researches on system reliability assessment have been performed or recommended [3-10], but it still lacks of an enough fast qualification method.

Since all LED light sources are already tested for luminous maintenance at package or module level, and the so-called LM-80 data are already provided, it may not be necessary to run lumen maintenance test at system level. Since LM-80 database has provided the relationship between lifetime and junction temperature, the way to predict the lifetime will be very fast if based on the maximum junction temperature of LED luminaire, instead of instead of running lumen maintenance test to extrapolate the lifetime.

In this work, a novel hybrid method, which combines the thermal modeling and temperature measurement, is proposed to estimate the junction temperature of high-power LEDs at system level, and therefore predict the lifetime of LED luminaries based on the known LM-80 data. First, a reference point at a luminaire system is selected to measure the temperature in the operating mode. Secondly, thermal modeling is performed to predict the junction temperature and the overall temperature distribution, with a goal to find a reliable relationship between the junction temperature and the reference point (measuring point). At the same time, to validate the predicted junction temperature, the thermal measuring experiments combined with thermal tester T3ster Master are implemented. Finally, the relationship between lifetime and junction temperature provided by the known LM-80 data is used to estimate the LED luminaire's lifetime.

2. Junction Temperature Measurement

The thermal performance is defined once a LED luminaire is built. It indicates that the thermal resistance from junction point to the heat sink surface has been decided, and therefore its life character is also designated.

The junction temperature of LED package can be calculated based on a one-dimension model (formula (1)) of thermal resistance easily [9].

$$T_j = T_{\Delta} + T_c = R_{th} \times P_h + T_i \quad (1)$$

Where,

T_i : Temperature of solder joint of LED package;

T_j : Junction temperature;

T_{Δ} : Thermal difference between T_j and T_c ;

R_{th} : Thermal resistance;

P_h : Heat generation rate;

However, the calculation (three-dimensions) of thermal resistance at a luminaire system is complex. It is unfeasible to setup thermal resistance model. To simplify such a complex process, the finite element modeling (FEM) is employed in this paper, with a goal to find a reliable relationship between the junction temperature and the reference point (measuring point). The thermal measuring experiments combined with the tester T3ster are carried out for validating the predicted junction temperature.

2.1 Thermal Modeling

One commercial 12-watt LED lamp, as shown in Fig. 1, is chosen as the modeling object in this paper. Its claimed lifetime is 45,000 hours, and defined as the number of hours when 50% of a large group of identical lamps below 70% of its initial lumens. To save the simulation time, a quarter-sized model is built and analyzed, as shown in Fig. 2.

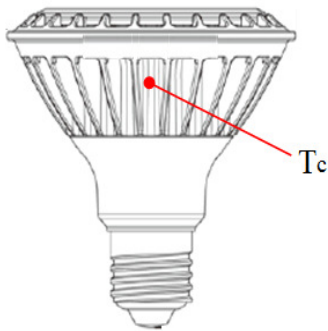


Fig.1 LED lamp outline

A reference point (T_c , measuring point) is selected on the heat sink, since its thermal sensitivity is stable to the junction temperature based on the thermal distribution. Both of Fig. 1 and Fig. 2 label out the T_c . Meanwhile, junction point (T_j) that is in the LED package with the highest temperature in the luminaire, solder joint point (T_d) below the LED substrate and a point (T_p) closed to the LED substrate and near the PCB of LED module are labeled. T_p is also the point where can be measured with a thermal couple.

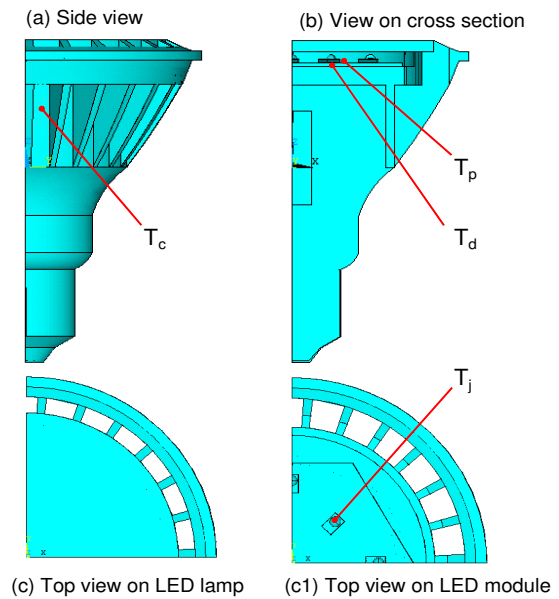


Fig.2 Quarter-sized modeling

Table 1 Overview of material properties

Materials	Thermal conductivity	Mass density	Specific heat
PC (Lamp cover)	0.16	1250	1700
Silicone	0.22	1200	1260
GaN	130	3965	730
Die-attach	57	7390	217
FR4	4	1100	1085
Cu	400	8950	390
Al (heat sink)	237	2700	880
Potting adhesive	0.68	1550	1230
TIM	1.8	3180	1239.29

The transient thermal transfer analysis is conducted on the quarter-sized modeling based on a database of material properties, as shown in table 1. The result shows the junction temperature rises dramatically at the beginning of operating. Fig. 3 presents the thermal distribution at various time points (3s, 100s, 200s, 1000s and 8000s). The thermal distribution becomes stable after about one hour.

Fig. 4 presents the temperature rises of those 4 points selected in the finite element model. It is found that all points balance finally at a constant temperature. And the temperature difference of any two points is steady, as shown in Fig. 5. The temperature difference between T_c and T_j reaches a constant (T_s) within 20 seconds, which suggests that the thermal resistance of any two points in luminaire can be simplified as a stable value, and similar as the known method in a LED package. Based on such a suggestion, the junction temperature of LED package with the highest temperature in the luminaire can be predicted based on the result of thermal modeling and the thermal profile of reference point (T_c).

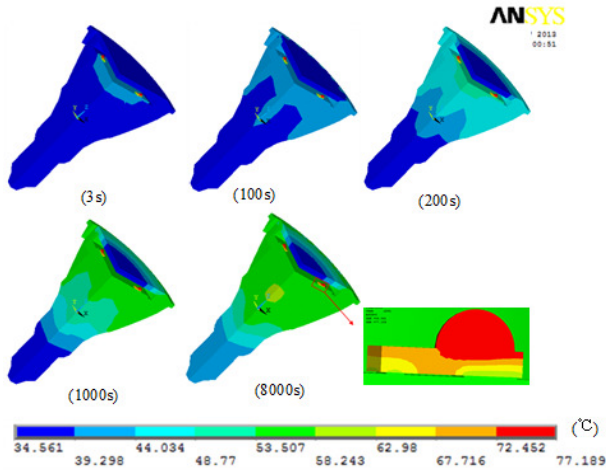


Fig. 3 Thermal distributions of quarter-sized modeling

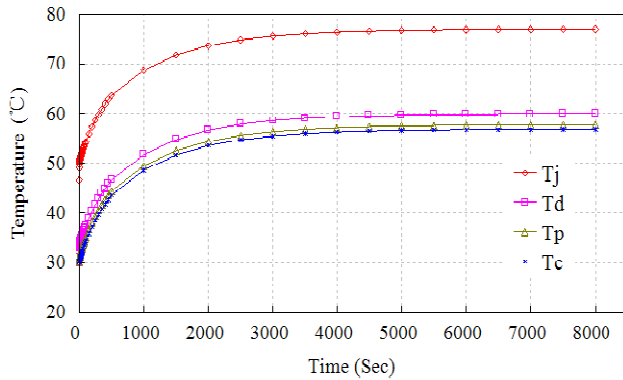


Fig.4 Temperature rise at different point (FEM result)

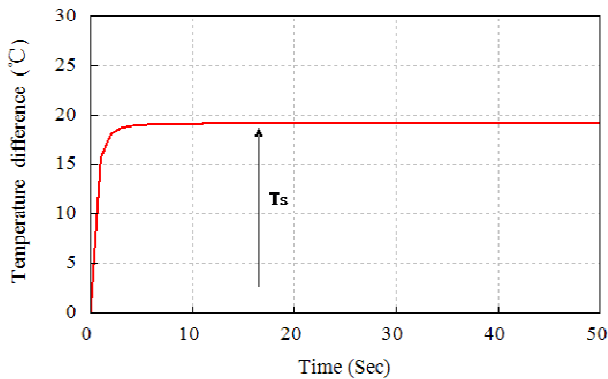


Fig. 5 Temperature difference between reference point and junction point (FEM result)

2.2 Thermal Measurement

To validate the above relationship between the junction temperature and the reference point (measuring point), one thermal couple is attached on the measuring point T_c , and another thermal couple is on the point T_p . Meanwhile, the thermal resistance of LED module is measured by the thermal tester T3ster Master.

Fig. 6 shows the cumulative structure functions of LED module. Results of two situations (P-1: LED module with

TIM1 and heat sink, P-2: LED module with TIM2 and heat sink) provide the thermal resistance between junction and LED substrate (above 3.326 K/W), and the thermal resistance (R_{th}) from junction to T_p is around 1.6 K/W. Since the P_h is 6.26W (from the analysis result of T3ster Master), the junction temperature can be calculated based on formula (2).

$$T_j = T_{\Delta} + T_p = R_{th} \times P_h + T_p = 1.6 \times 6.26 + T_p \quad (2)$$

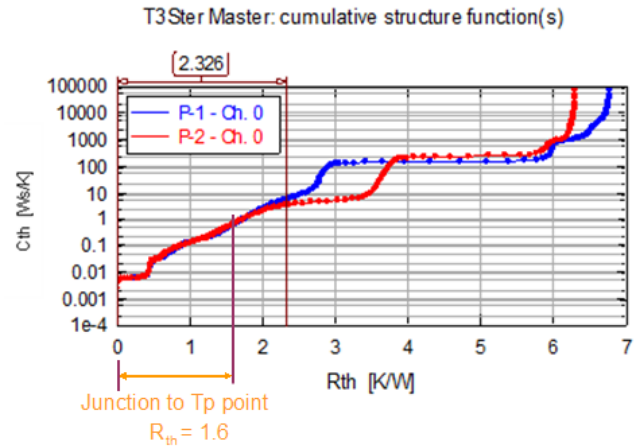


Fig. 6 Cumulative structure functions of LED module

Fig. 7 shows the junction LED temperature predicted according to the measured profile of the point T_p . And the temperature difference from T_j to T_c is shown in Fig. 8. It is extremely obvious that the temperature difference reaches to a steady value (T_s), which is similar as the FEM result. Both of steady time point and value have a slight offset to the result of FEM, which is resulted from the database deviation of material properties. It is found that the predicted junction temperature deviation to the actual one is from 2 to 5 °C.

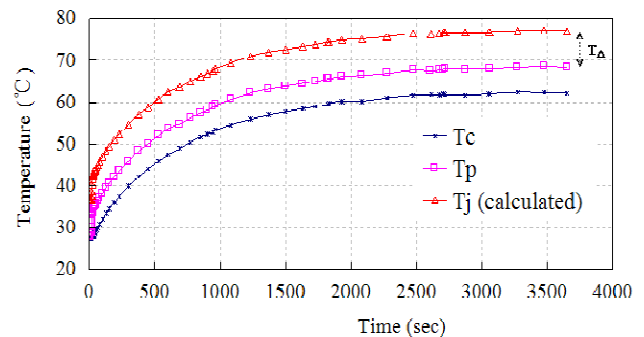


Fig. 7 Temperature rise at different points (T_c and T_p are the experimental results, and T_j is calculated with the formula (2))

2.3 Method summary of junction temperature measurement

After a luminaire operates to a steady situation, the thermal resistance between T_c and T_j can be simplified as a stable value so that and hereby the complex modeling of thermal resistance is simplified into one dimension model, as shown in Fig. 9.

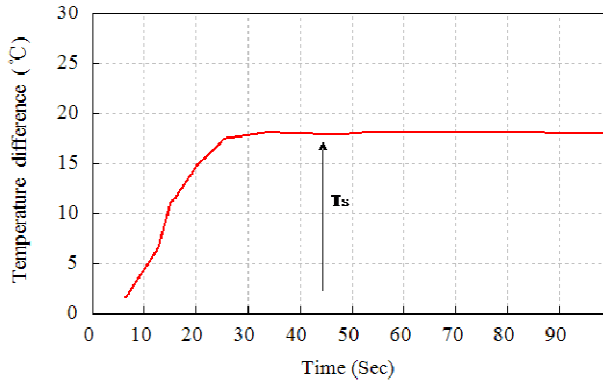


Fig. 8 Temperature difference between the measuring point and the calculated junction point

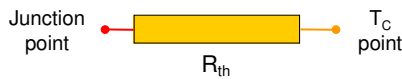


Fig. 9 Thermal resistance modeling at steady operating

The temperature difference between T_c and T_j also reaches a constant (T_s), and the junction temperature can be obtained based on the temperature of a measuring point (T_c), which can be described as below formula (3).

$$T_j = T_s + T_c \quad (3)$$

T_s is a temperature difference and calculated by FEM according to a credible database of material properties. It is also easy to understand that T_s presents the capability of heat dissipation of a luminaire. T_c is a value from the thermal profile of a typical measuring point on LED luminaire, and measured by thermal couple.

According to the thermal modeling and measurement, the junction temperature of LED lamp used in this paper is 78°C approximately as below formula (4). For the actual situation, the junction temperature should be $75\sim 80^\circ\text{C}$.

$$T_j = T_s + T_c = 17.22 + 61.24 = 78.46^\circ\text{C} \quad (4)$$

3. Lifetime Prediction

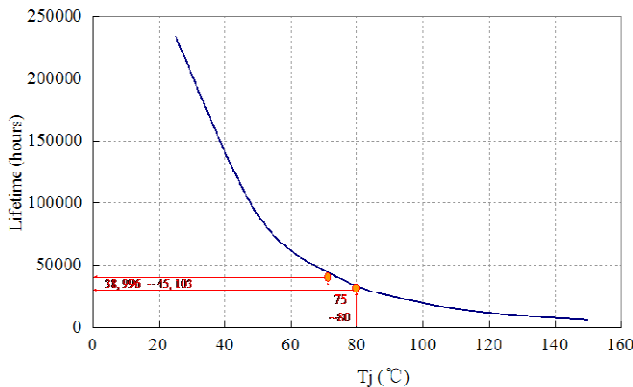


Fig. 10 Lifetime prediction based on junction temperature

The known LM-80 data already provided the relationship between lifetime and junction temperature so that the lifetime of LED luminaires can be predicted based on the predicted junction temperature, instead of running lumen maintenance test at system level to extrapolate. According to the proposed method of junction temperature measurement, the lifetime the luminaire's lifetime can be predicted. As shown in Fig.10, the LED lamp lifetime is forecasted between 38,996 and 45,103 hours, which meets the lifetime (45,000 hours) estimated by manufacturer.

Currently, further verification studies are ongoing, such as involving in more types of LED luminaires, and combined with reliability testing. The proposed method is expected to be very useful in future LED luminaire qualification test specification.

4. Conclusions

A novel hybrid method, which combines the thermal modeling and temperature measurement, is proposed to estimate the junction temperature of high-power LEDs at system level, and therefore predict the lifetime of LED luminaire based on the known LM-80 data. Since the modeling (three-dimensions) of thermal resistance at a luminaire system is complex, the finite element modeling is employed, with a goal to find a reliable relationship between the junction temperature and the reference point (measuring point). At the same time, to validate the predicted junction temperature, the thermal measuring experiments combined with the thermal tester T3ster are implemented. Finally, the relationship between lifetime and junction temperature provided by the known LM-80 data is used to estimate the LED luminaire's lifetime.

It is found that, after a luminaire operates to a steady situation, the temperature change between the measuring point and the junction point reaches a constant, which indicates the thermal resistance between them can be simplified as a stable value so that the complex modeling of thermal resistance is simplified into one dimension situation. Therefore, the junction temperature of a luminaire can be obtained based on the temperature measurement of a measuring point and the thermal modeling. The application of proposed method implied that the predicted lifetime meets closely the lifetime estimated by vendor. The proposed method is expected to be very useful in future LED luminaire qualification test specification, instead of running lumen maintenance test at system level to extrapolate the lifetime.

Acknowledgments

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References

- [1] S. Tarashioon, A. Baiano, et al. An approach to "Design for Reliability" in solid state lighting systems at high

- temperatures. *Microelectronics Reliability*, 52(5), 2012, 783-793.
- [2] U.S. Department of Energy. Solid-State Lighting Research and Development. Manufacturing Roadmap, July 2011.
- [3] Bong-Min Song, Bongtae Han et al. Hierarchical Life Prediction Model for Actively Cooled LED-Based Luminaire. *IEEE transactions on components and packaging technologies*, 33(1), 2010, pp: 728 - 737.
- [4] S. Koh, W.D. van Driel, et al. Solid State Lighting System Reliability. *ChinaSSL*, 2011, pp:121-126.
- [5] W.D. van Driel, C.A. Yuan et al. LED System Reliability. *EuroSimE 2011*, 2011, pp: 1/5 - 5/5.
- [6] X. P. Li, L. Chen, M. Chen. An approach of LED lamp system lifetime prediction. *ICQR*, 2011, pp:110-114.
- [7] W. D. V. Driel, F. Evertz and G. Q. Zhang. Towards a System Level Reliability Approach for Solid State Lighting. *Journal of Light and Visual Environment*, 35 (3), 2011, pp: 267 – 273.
- [8] M. Cai, D. G. Yang, S. Koh et al. Accelerated Testing Method of LED Luminaries. *EuroSimE 2012*, 2012, pp: 1/6-6/6.
- [9] EIA/JESD51-1. Integrated Circuit Thermal Measurement Method Electrical Test Method (Single Semiconductor Device) [S].
- [10] van Driel WD, Fan XJ (Eds.). *Solid State Lighting Reliability: Components to System*. Springer, New York. 2012.