

Thermal Uniformity Improvement of High Power LED Street Lamp Using Nonuniform Distribution Design of LEDs

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Abstract. Light emitting diode (LED) street lamp heavily relies on successful thermal management, which strongly affects the optical extraction and the reliability/durability of the LED lamp. In this study, the two-dimensional temperature profile of a high power LED street lamp with traditional uniform distribution of LEDs is calculated, which shows that there is a higher temperature in the central region of the heat sink. For the 196 watts LED street lamp, the peak heat sink temperature was about 53.2°C at the environment temperature of 20°C. With the aid of the theoretical analysis, an optimized structure of LED street lamp with nonuniform distribution of LEDs is presented. The peak temperature is lowered by 1°C compared with that of the uniform one. And the temperature difference within 0.1°C in the surface of aluminum plate. The improvement above is ascribed to the nonuniform distribution of LEDs, and hence suppressing the heat flow from adjacent area to the central area. Therefore, the calculated results verify that the optimized structure of high power LED street lamp with nonuniform distribution of LEDs is superior to the uniform distribution of LEDs for enhancing the thermal uniformity of LED street lamp.

Keywords: high power LED street lamp; nonuniform distribution; thermal uniformity;

1. Introduction

Theoretically, light emitting diode (LED) has many distinctive advantages such as high efficiency, good reliability, long life, variable color and low power consumption. There have been lots of references to study high power LED. Wilcoxon and Cornelius^[1] described the thermal management approach to a light engine and presented the results of their finite element modeling. Kim et al.^[2] investigated the performance of thermal management system for LED light source in a rear projection TV. Liu's group^[3, 4, 5] studied a micro jet array cooling system for the thermal management of a high power LED lighting source. Treurniet and Lammens^[6] presented a thermal design method of a multichip LED module that was able to handle an increasing thermal load up to 20 Watts. Tan, Liuxi et al.^[7] studied the effects of various defects in terms of voids, cracks, delaminations on the thermal and optical performance of LEDs subjected to both powering and moisture loadings. Recently, LED has begun to play an important role in many applications^[8]. One typical general lighting product of LED is LED street lamp, which is emerging in market, in particular in China. For modern LED street lamps, the thermal management is a critical factor for their high performance, which is particularly important for high power LED street lamps where the self-heating in each LED and the thermal coupling among the LEDs lead to a nonuniform temperature profile. Narendran and Gu^[9] have experimentally demonstrated that the life of LEDs decreases with the increase of the junction temperature in an exponential manner. Therefore, the LEDs in higher temperature area have shorter life and lower reliability than the others in lower temperature area, which reduces the reliability of the high power LED street lamp.

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In order to improve the uniformity of the temperature profile, the technology of nonuniform distribution design of LEDs is studied and the simulated temperature profile is presented assumed that the temperature in a given LED is uniform and each LED has only one heat-source cell in this research. And the simulated results exhibit that, the nonuniform distribution design of LEDs is very effective for improving the uniformity of the temperature, and hence enhancing the reliability of the high power LED street lamp.

2. Thermal Model and Theory

Fig.1 is the three-dimensional schematic diagram of the high power LED street lamp. This lamp is mainly composed of three parts: high power LED modules, a mechanical frame for heat dissipation, and a thin aluminum plate for support of the LED modules. The lamp frame consists of aluminum base and fins, which are made as one integrated design for saving fabrication cost and decreasing thermal resistance. Each LED is set as a heat-source cell to simplify the model. The current and the temperature are uniform over the surface of each individual heat-source cell.

In this paper, only tow-dimensional temperature profile on the surface of aluminum plate is considered. Fig.2 is the schematic diagram of the distribution of LEDs. As shown in Fig.2, one hundred and ninety six LED modules are directly bonded on the aluminum plate for reducing thermal resistance. They are distributed on the heat sink base in 7×28 matrix. The one hundred and ninety six LED modules are the same, their default input powers are 1 watt. However, there are only about 0.9 watts power converted into heat. Therefore, the total thermal power for this model is about 174.6 watts.

For the lamp, when the electronic power is supplied, LEDs generate light and also heat. The heat is dissipated out into the environment through the aluminum base and fins on the base.

In a steady state, the temperature on the surface of aluminum plate can be governed by the following equation ^[10]:

$$\frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} + \frac{\partial^2 T}{\partial z^2} = 0 \quad (1)$$

And the following set of appropriate boundary conditions:

$$T|_{x,y,z=\infty} = T_a \quad (2)$$

$$\frac{\partial T}{\partial x} \Big|_{x=0,l} = 0 \quad (3)$$

$$\frac{\partial T}{\partial y} \Big|_{y=0,w} = 0 \quad (4)$$

Where T_a is the ambient temperature, l is length of aluminum plate, w is width of aluminum plate.

Equation (1) can be solved using the boundary conditions given by (2)-(4).

3. Simulation Result and Analysis

Fig.3 shows the simulated temperature on the plate surface of the heat sink with uniform distribution of LEDs at 0.9 watts thermal power of each LED, where the heat sink exhibits the highest temperature of 53.2°C in the central area of the street lamp at the environment temperature of 20°C . The temperature profile on the plate surface is a two-dimensional Gaussian function, which is given by (5).

$$T = T_0 + Ae^{-\frac{1}{2}\left(\frac{(x-x_c)^2}{w_1^2} + \frac{(y-y_c)^2}{w_2^2}\right)} \quad (5)$$

Where $(x_c, y_c) = (341.5, 141.5)$ is the center coordinates on the surface of aluminum place. By fitting the temperature profile in Fig.3, $T_0 = -6573.4$, $A = 6626.6$, $w_1 = 18646.3$ and $w_2 = 6904.8$.

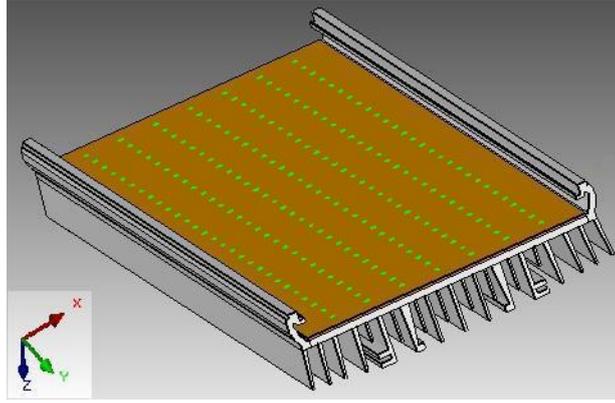


Fig.1 Schematic diagram of the LED street lamp

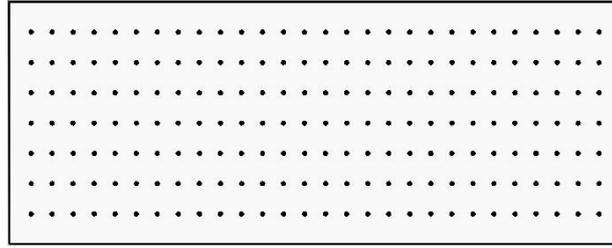


Fig. 2 Schematic diagram of the distribution of LEDs

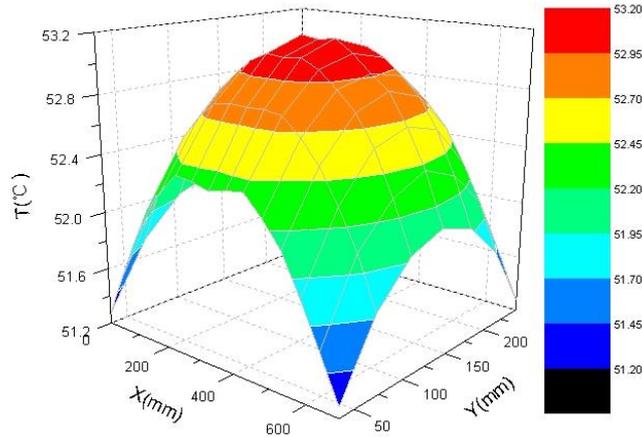


Fig.3 The calculated temperature profile on the plate surface with uniform distribution of LEDs

Because of the effect of junction temperature on the life of LED, the LEDs in the central area have shorter life and lower reliability than the others, which reduces the reliability and eventually gives rise to permanent damage of the high power LED street lamp.

In order to reduce the temperature in the central area and improve the thermal uniformity of the high power LED street lamp, an improved nonuniform distribution of LEDs is designed based on the criterion that all the LEDs exhibit approximate temperature at a given power. The heat flux of the improved distribution of LEDs should be contrary to the temperature profile, thus it makes the temperature profile on the plate surface to be uniform. An auxiliary function is created to obtain the heat flux function. The average of the auxiliary function and the temperature distribution function should be equal to 52.2°C , which is the average temperature on the plate surface (T_{ave}). Therefore, the auxiliary function also should be a two-dimensional Gaussian function, and the index of e is same to temperature distribution function. The auxiliary function is given by (6).

$$T' = T_0' + A' e^{-\frac{1}{2} \left(\frac{(x-x_c)^2}{w_1^2} + \frac{(y-y_c)^2}{w_2^2} \right)} \quad (6)$$

Therefore,

$$\begin{aligned}
T_{ave} &= \frac{T + T'}{2} \\
&= \frac{1}{2} \left(T_0 + A e^{-\frac{1}{2} \left(\frac{(x-x_c)^2}{w_1^2} + \frac{(y-y_c)^2}{w_2^2} \right)} \right. \\
&\quad \left. + T_0' + A' e^{-\frac{1}{2} \left(\frac{(x-x_c)^2}{w_1^2} + \frac{(y-y_c)^2}{w_2^2} \right)} \right) \\
&= 52.2
\end{aligned}$$

Thus,

$$\frac{T_0 + T_0'}{2} = 52.2$$

$$A + A' = 0$$

Where

$$T_0 = -6573.4$$

$$A = 6626.6$$

Thus,

$$T_0' = 6677.8$$

$$A' = -6626.6$$

The heat flux function which is given by (7) should be proportional to the auxiliary function.

$$q = q_0 + B e^{-\frac{1}{2} \left(\frac{(x-x_c)^2}{w_1^2} + \frac{(y-y_c)^2}{w_2^2} \right)} \quad (7)$$

The average temperature and heat flux on the plate surface is about 52.2°C and 0.1W/cm², respectively. Scale factor is 522, thus

$$q_0 = \frac{T_0'}{522} \approx 12.7927$$

$$B = \frac{A'}{522} \approx -12.6946$$

Fig.4 shows the heat flux profile on the plate surface with nonuniform distribution of LEDs, which is given by (7). Fig.5 shows the schematic diagram of the nonuniform distribution of LEDs.

The calculated temperature profile on the plate surface of the heat sink is shown in Fig.6. As shown in Fig.6, the peak heat sink temperature is about 52.2°C, which is lowered by 1°C compared with that of the uniform one. And the temperature difference within 0.1°C in the surface of aluminum plate. Therefore, this distribution improved thermal uniformity of the street lamp.

4. Summary

Two-dimensional temperature profiles of high power LED street lamp with traditional uniform distribution of LEDs and nonuniform distribution of LEDs (optimum design) are calculated, which are assumed that each LED is a heat source with constant heat flow. The calculated results show that LED street lamp with nonuniform distribution of LEDs could lower the peak temperature and improve the uniformity of the temperature profiles effectively. The results of this work provide useful guidelines for designing high power LED street lamp with thermal uniformity.

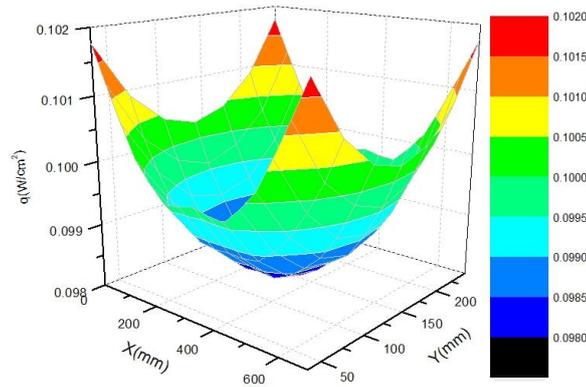


Fig. 1 The heat flux profile on the plate surface with nonuniform distribution of LEDs

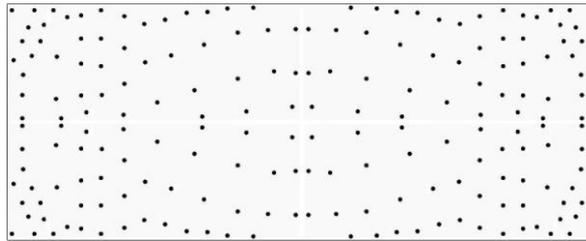


Fig. 2 Schematic diagram of the nonuniform distribution of LEDs

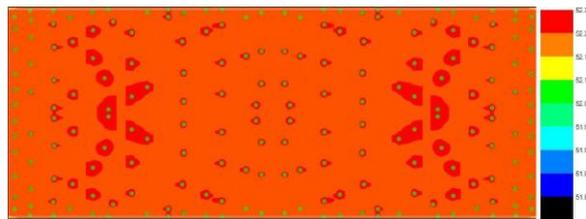


Fig. 3 The calculated temperature profile on the plate surface with nonuniform distribution of LEDs

5. Acknowledgment

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