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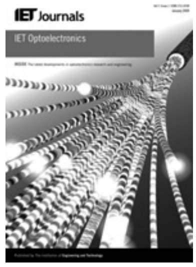

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Temperature estimation of high-power light emitting diode street lamp by a multi-chip analytical solution

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Abstract: Light emitting diodes (LEDs) are now widely used in many fields including traffic lights, vehicle backlights and liquid crystal display (LCD) displays because of their long life, good illumination efficiency and low energy consumption. At present, LEDs are increasingly replacing the traditional lighting and are being used in general illumination such as the street lamp. For the high-power LED street lamps, good light extraction is the most important thing, but low junction temperature of the LED modules is also critical for achieving a long lifetime and a high optical efficiency. Actually, there have been many reports about early failures of street lamps, called dead lamps that have been regarded as a barrier in the public and administration acceptance of LED street lamps. Therefore temperature estimation is always a crucial issue for LED product development. A multi-chip spreading thermal resistance model was applied to estimate the temperature distribution of LED street lamp. The experiment was first done to obtain temperatures of several locations in a prototype LED street lamp. Then the multi-chip spreading resistance model was established to calculate the full temperature distribution. Comparison between the model calculation and experimental measurement showed a good agreement, which demonstrates that the present model can be used in engineering design to estimate the temperature distribution of high-power LED street lamps.

Nomenclature

a	the length of heat sink, m
b	the width of the heat sink, m
c	the length of heat source, m
d	the width of heat source, m
h	heat transfer coefficients, W/m^2 K
k_1	thermal conductivity of the heat sink, W/m K
m	index
n	index
Q	heat flux, W
T	heat sink temperature, $^\circ$C
t_1	the thickness of heat sink, m
tf	ambient temperature, $^\circ$C
(X_c, Y_c)	coordinate of heat source, m,m
(x, y)	coordinate of each location, m, m
θ	excess temperature $\equiv T -$ tf, K

1 Introduction

Light emitting diode (LED) differs from conventional light sources; it provides a direct transfer of electrical energy into light. Although there are many lighting technologies, LED has been foreseen as an 'ultimate lamp' for the future [1].

Theoretically, LED has many distinctive advantages such as high efficiency, good reliability, long life, variable colour and low power consumption. Recently, LED has begun to play an important role in many fields, so that LED products are now being used in many fields including traffic lights, vehicle headlights and backlights, LCD displays and street lamps and so on [2]. LED is expected to be used in general lighting, which consumes about 15% of the total energy around the world. It is believed that high-power LED will be the dominant lighting technology by 2025 [3].

High-power LEDs in operation can produce high luminance, but they also generate significant heat at the same time. It has been reported that the optical output of the LED is sharply degraded with the increase in junction temperature [4] because the high temperature significantly influences the reliability and durability of the LED [5]. Therefore effective thermal design and reliable thermal characterisation of LED system are some key factors in LED design considerations. For high reliability, it is critical that maximum specified operating junction temperatures are not exceeded.

So far, LED street lamps are usually composed of many high-power LED modules. With higher chip densities, thermal management of the LED street lamp proposes a big challenge to the street lamp design and manufacturing. There is a need to define the junction-to-ambient and junction-to-case thermal resistances for multi-chip modules in a more rigorous manner and provide information to predict junction temperatures under arbitrary powering up of individual chips.

There are few direct references to do the thermal estimation of multi-chip packaging in LED and LED street lamp field. But some investigations have been conducted to solve this problem in the electronics packaging field since the same challenges are also faced in electronics packaging field. Kim and Shin [6] discussed transient thermal measurements of high-power GaN-based LEDs with multi-chip designs. The structure function theory was applied to determine the thermal resistance of LED packages. The total thermal resistance of multi-chip packages was found to decrease with the number of chips because of parallel heat dissipation. However, the effect of the chip number on the thermal resistance of the package strongly depends on the ratio of partial thermal resistance of chip and that of slug under the chip. Lall *et al.* [7] performed some experiments for non-uniform powering up of a multiple-chip module mounted on a vertical board in natural convection. The average chip temperature because of multiple sources within the module was considered as the reference temperature for evaluating the junction temperature rise of a particular chip. This approach offered a more refined methodology for evaluation of non-uniformly powered multi-chip modules compared to previous methods. Im *et al.* [8] developed a new approach to determine the junction temperatures of the system in packaging (SiP) and the temperature difference from the average temperature was calculated by linear superposition. The 'hot spot factor', which could reflect the effect of chip size and hot spot on the chip, was newly proposed. Using this approach, one can calculate device junction temperatures simply and accurately. Zahn [9] discussed how a central composite design of experiments can be applied to provide a more accurate thermal characterisation of a multi-chip module package. The end product was a series of linear or polynomial equations that could be utilised by the customer to calculate individual device junction temperatures over a wide variation of convection cooling environments and multiple device power dissipations.

The present authors have already done some researches about temperature estimation of LED, a simple engineering method to calculate junction temperature based on spreading thermal resistance was mentioned in [10]. Based on this work, the thermal resistance network of LED street lamp was proposed in [11], in which single-chip thermal spreading resistance was considered. Different from the aforementioned works, in this paper, a multi-chip thermal spreading resistance model was established to estimate LED mounted-base temperature distribution. The effect of different chips on each other was considered. Also, the present model can easily obtain the total temperature distribution in LED chip board.

Except the new model introduction, the thermal behaviour of a 114-W LED street lamp was investigated based on the present method in this paper. The modelling results were compared with the experimental measurements, which demonstrated that this method could predict the temperature distribution of the heat sink base of LED street lamp and could be further used to evaluate the LED chip junction temperature.

2 Model of one typical high-power LED street lamp

Fig. 1 shows the schematic diagram of 114-W LED street lamp made in the authors' lab. Fig. 2 shows the details of heat sink used in the 114-W lamp [11]. The lamp is mainly composed of three parts: high-power LED modules, a mechanical frame for both the heat dissipation and support of the LED modules, and several printed circuit boards (PCBs) for the power input of LEDs. The lamp frame consists of aluminium base and fins. Ninety-six high-power LED modules are bonded onto the heat sink. They are distributed on the heat sink base in eight rows. The default input powers of the 96 LED modules are 1 W; however, here they are supplied with 1.188-W power, and therefore the total input power for this lamp is about 114 W. When the electronic power is supplied, LEDs generate both light and heat. The heat is dissipated into the environment through the aluminium base and fins on the base.

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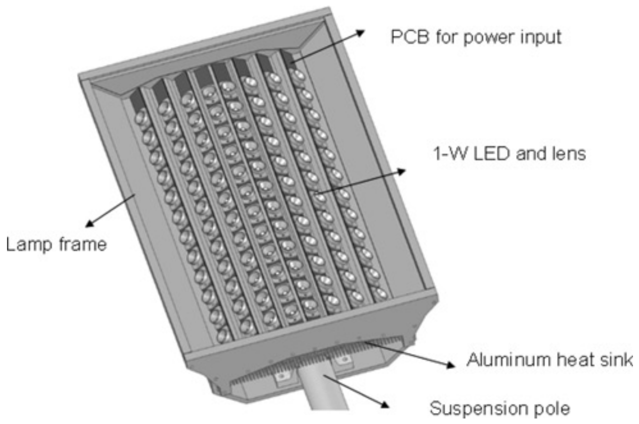

Figure 1 *Schematic diagram of 114-W LED street lamp*

3 Temperature test of the 114-W LED street lamp

The temperature distributions of the 114-W LED street lamp were measured by T-type thermocouples in the experiments. Fig. 3 shows the experimental setup. The orientation of the heat sink and the system was set according to the application conditions. The fin bases were placed in the bottom whereas the fin tips were on the top. Tests were conducted under a natural environment with an ambient temperature of about 25.0 °C. Several thermocouples were placed at different positions of the aluminium base and fins. The temperature data obtained by the thermocouples were transferred to the data acquisition system Keithley 2700 multimeter and displayed on the PC monitor.

In the experiments, the temperature was the main parameter for system evaluation, and it was directly measured by thermocouples. Since there were no other indirectly measured parameters, the errors associated with this experiment mainly included measurement error of the thermocouples and reading error of the digital multimeter. Standard T-type thermocouples (Cu–CuNi) were used in the experiments. During the temperature range from −30.0 to 150.0 °C, the measurement error of T-type thermocouples was about 0.2 °C. The data acquisition system had a reading error of 1.0 °C since the cold junctions of the thermocouples used the default setup supplied by the system, not the ice bath with constant 0 °C. Therefore the total error of the temperature measurement for the experiments was about 1.2 °C.

When the temperature reached balance for a certain time, the results were acquired through the thermocouples that are shown in Fig. 4 and Table 1. As it was difficult to show the temperature change of all the thermocouples, so only several points' temperatures were chosen to show this trend. It is found from Fig. 4 and Table 1 that the averaging temperature of fins and base is 60.9 °C, and the maximum temperature of fins and base, which bonds with the LED chips, is 61.7 °C.

Obviously, only the temperatures of several points on the heat sink were obtained by the experimental tests because of space distribution limitation and limited numbers of thermocouples. If the total heat sink temperature distribution needs to be known, some other methods should be found to predict the temperature distribution.

4 Multi-chips thermal spreading resistance model

The thermal resistance network model to estimate the chip junction temperature was mentioned in our previous paper

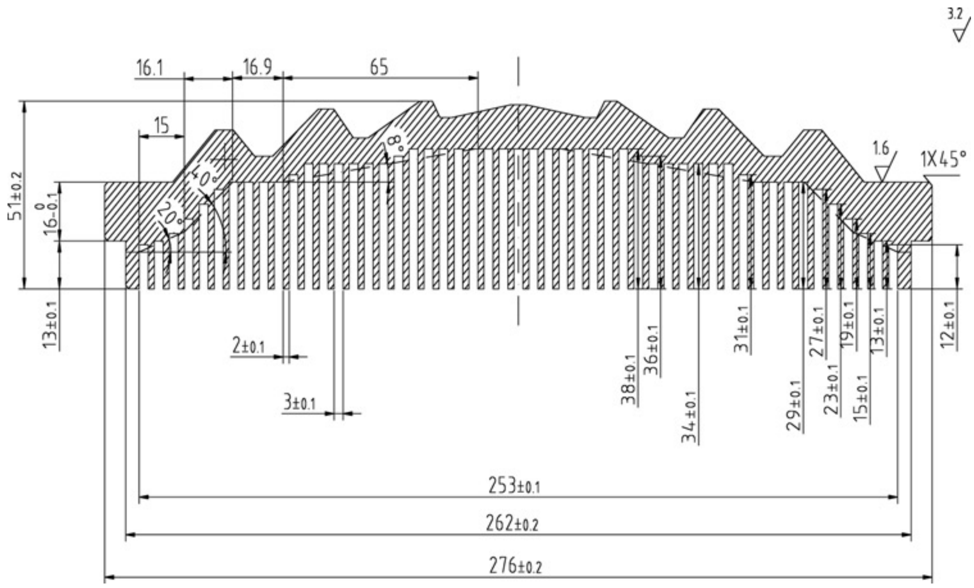

Figure 2 *Details of heat sink used in the 114-W lamp (all dimensions are in mm)*

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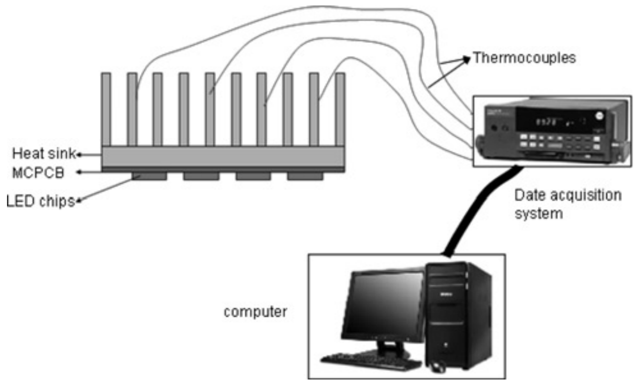

Figure 3 *Experimental setup*

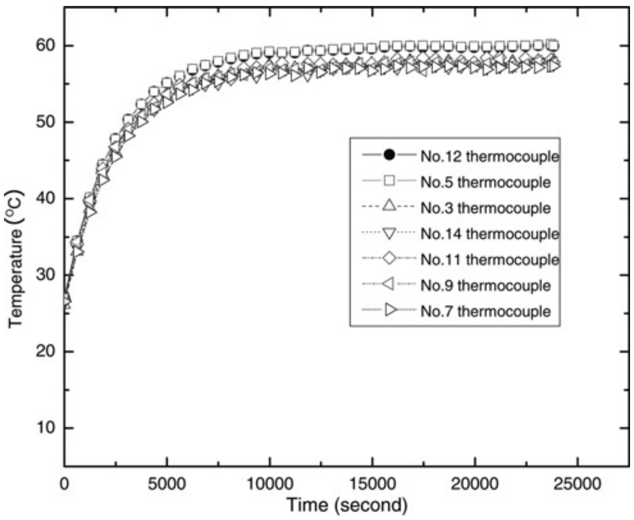

Figure 4 *Variation of the heat sink temperature with the operation time for 114-W street lamp*

[11] in which the thermal spreading resistance of the high-power LED street lamp was introduced. However, in that paper, the spreading thermal resistance model was based on the single-chip thermal spreading resistance. The thermal effect of one chip on another chip was not considered. In the present paper, multi-chips thermal spreading resistance model will be built. To clearly present the model, the temperature distribution equation based on thermal spreading resistance will be introduced from a single chip to multiple chips.

4.1 Single-chip structure

The module is shown in Fig. 5, the heat source area is $c \times d$ and its power is Q which is dissipated by the heat sink whose area is $a \times b$ with thickness t_1. The centre coordinate of heat source is (X_c, Y_c). The surrounding of the heat sink is isolated, the bottom part of the heat sink exchanges heat with environment by natural convection, the heat transfer coefficient between the heat sink and the ambient is h, the thermal conductivity of the heat sink is k_1 and the ambient temperature is tf.

The boundary conditions of the model are:

For the boundaries where $x = 0$ and a

$$\frac{\partial T}{\partial x} = 0 \tag{1}$$

At the positions where $y = 0$ and b

$$\frac{\partial T}{\partial y} = 0 \tag{2}$$

where T is the temperature, x and y are the coordinates. The average excess temperature of the chip $\bar{\theta}$ can be obtained through the following expressions [12–16]

$$\begin{aligned}\bar{\theta} = {} & \bar{\theta}_{1D} + 2\sum_{m=1}^{\infty} A_m \frac{\cos(\lambda_m X_c)\sin(1/2\lambda_m c)}{\lambda_m c} \\ & + 2\sum_{n=1}^{\infty} A_n \frac{\cos(\delta_n Y_c)\sin(1/2\delta_n d)}{\delta_n d} \\ & + 4\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{mn} \frac{\cos(\delta_n Y_c)\sin(1/2\delta_n d)\cos(\lambda_m X_c)\sin(1/2\lambda_m c)}{\lambda_m c \delta_n d}\end{aligned} \tag{3}$$

where m and n are the indices, which are suggested to be 100 to obtain a certain accuracy because of the complicated calculations, the other parameters are given as the follows

$$\bar{\theta}_{1D} = A_0 = \frac{Q}{ab}\left(\frac{t_1}{k_1} + \frac{1}{h}\right) \tag{4}$$

$$\lambda = m\pi/a \tag{5}$$

$$\delta = n\pi/b \tag{6}$$

$$\beta = \sqrt{\lambda^2 + \delta^2} \tag{7}$$

$$\phi(\varsigma) = \frac{\varsigma \sinh(\varsigma t_1) + h/k_1 \cosh(\varsigma t_1)}{\varsigma \cosh(\varsigma t_1) + h/k_1 \sinh(\varsigma t_1)} \tag{8}$$

Table 1 Experiment temperature data of 114-W LED street lamp

Power, W	Ambient temperature, °C	Average heat transfer coefficient of fins and base (h), W/m^2 K	Average temperature of fins and base, °C	Maximum temperature of fins and base, °C
114	25.0	1.5	60.9	61.7

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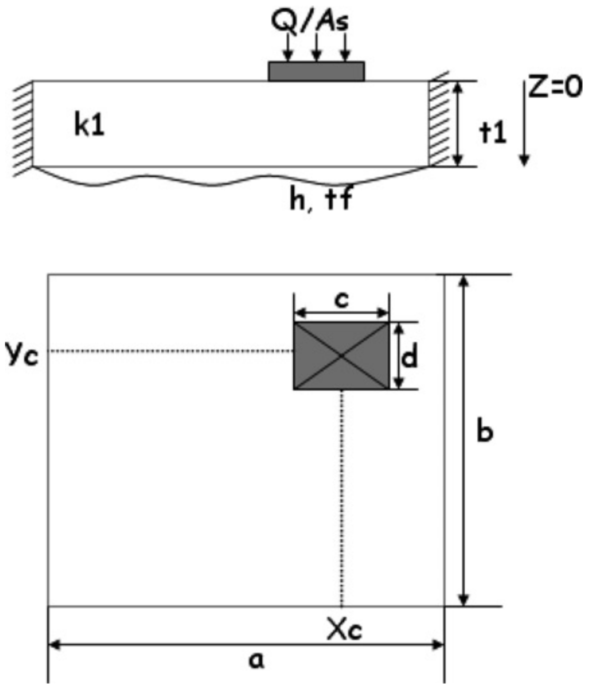

Figure 5 *Single-chip structure model*

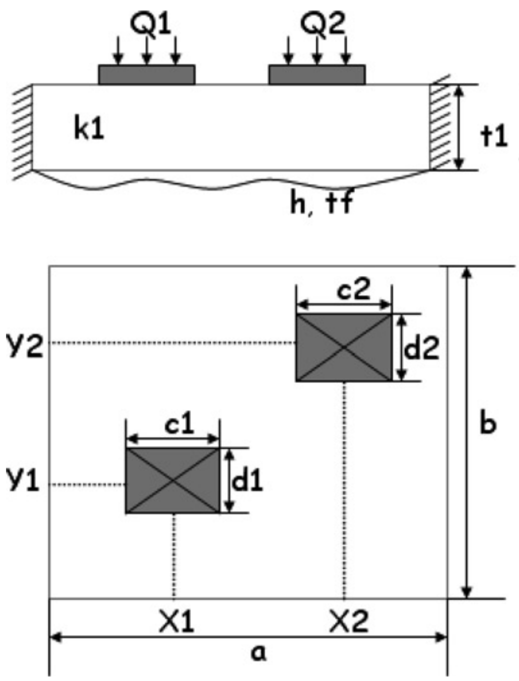

Figure 6 *Double-chip structure model*

where in the following expressions ς is replaced by λ, δ or β accordingly. Here h is the heat transfer coefficient, which is usually obtained by empirical equations provided by the experiments conducted by other researchers

$$A_m = \frac{2Q[\sin((2X_c + c)/2\lambda_m) - \sin((2X_c - c)/2\lambda_m)]}{abck_1\lambda_m^2\phi(\lambda_m)} \tag{9}$$

$$A_n = \frac{2Q[\sin((2Y_c + d)/2\delta_n) - \sin((2Y_c - d)/2\delta_n)]}{abck_1\delta_n^2\phi(\delta_n)} \tag{10}$$

$$A_{mn} = \frac{16Q\cos(\lambda_m X_c)\sin(1/2\lambda_m c)\cos(\delta_n Y_c)\sin(1/2\delta_n d)}{abck_1\beta_{m,n}\lambda_m\delta_n\phi(\beta_{m,n})} \tag{11}$$

4.2 Multiple-chip structure

To introduce the temperature distribution model of multiple-chip structure, the double-chip model was presented first.

The double-chip structure model is shown in Fig. 6, the heat source areas are $c1 \times d1$, $c2 \times d2$ and their powers are $Q1$ and $Q2$, respectively, which are dissipated by the heat sink whose dimensions are $a \times b$ with thickness of t_1. The central coordinates of the heat sources are ($X1$, $Y1$) and ($X2$, $Y2$), the surrounding of the heat sink is insulated. The heat transfer coefficient between the heat sink and the ambient at the bottom part of the heat sink is h, the thermal conductivity of the heat sink is k_1, and the ambient temperature is tf.

Based on the aforementioned single-chip model, the excess temperature distribution $\theta_i(x, y, 0)$ at the $z = 0$ surface can be expressed as the following equation [16]

$$\theta_i(x, y, 0) = A_0^i + \sum_{m=1}^{\infty} A_m^i \cos(\lambda x) + \sum_{n=1}^{\infty} A_n^i \cos(\delta y), \quad i = 1, 2$$
$$+ \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{nm}^i \cos(\lambda x)\cos(\delta y) \tag{12}$$

where $A_0 = \bar{\theta}_{1D}$ and others are the same as the single-chip model and (x, y) means every point on the heat sink surface contacting with heat sources. The parameters A_m, A_n and A_{mn} appeared in (9), (10) and (11), respectively, are composed of the heat source's dimensions. For double-chip structure, the excess temperature of each chip could be obtained by (12) and the corresponding two values of $\theta_i(x, y, 0)$ will be added together to obtain the total excess temperature $\theta(x, y, 0)$.

If there are several heat sources, all the temperature results for each heat source should be obtained and added together to attain the final result. For example, if the number of the heat sources is n, to obtain excess temperature distribution $\theta_i(x, y, 0)$ at the $z = 0$ surface, (12) should be added for n times and the parameters A_0, A_m, A_n and A_{mn} are different for every heat source, there are a group of A_0 (the value of A_0 is not changed), A_m, A_n and A_{mn} by (4), (9), (10) and (11), respectively. Therefore the excess temperature distribution at the $z = 0$

surface can be attained by (13)

$$\begin{aligned}\theta(x, y, 0) = {} & (A_0^1 + A_0^2 + A_0^3 + \cdots + A_0^n) \\ & + \left(\sum_{m=1}^{\infty} A_m^1 \cos(\lambda x) + \sum_{m=1}^{\infty} A_m^2 \cos(\lambda x) \right. \\ & \left. + \sum_{m=1}^{\infty} A_m^3 \cos(\lambda x) + \cdots + \sum_{m=1}^{\infty} A_m^n \cos(\lambda x)\right) \\ & + \left(\sum_{n=1}^{\infty} A_n^1 \cos(\delta y) + \sum_{n=1}^{\infty} A_n^2 \cos(\delta y) \right. \\ & \left. + \sum_{n=1}^{\infty} A_n^3 \cos(\delta y) + \cdots + \sum_{n=1}^{\infty} A_n^n \cos(\delta y)\right) \\ & + \left(\sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{mn}^1 \cos(\lambda x)\cos(\delta y) \right. \\ & + \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{mn}^2 \cos(\lambda x)\cos(\delta y) \\ & + \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{mn}^3 \cos(\lambda x)\cos(\delta y) \\ & \left. + \cdots + \sum_{m=1}^{\infty}\sum_{n=1}^{\infty} A_{mn}^n \cos(\lambda x)\cos(\delta y)\right) \end{aligned} \tag{13}$$

Based on (13), it is noted that the excess temperature distribution for multiple-chip structure can be expressed as similar as the double-chip structure; however, the more adding exists in multiple-chip structure calculation.

5 Temperature calculation of 114-W LED street lamp

The temperature of every location on the heat sink could be obtained through (12), it concerns about the effect of every heat source. In this equation, i means heat source index, A_m, A_n and A_{mn} are given from (9) to (11), $A_0 = \bar{\theta}_{1D}$ is given in (4), other parameters are given in (5)–(8) and more details could be found in [16].

For the 114-W LED street lamp, 96 high-power LED modules are distributed on the heat sink, which is shown in Fig. 7. The diameter of each module is 0.005 m and the input power is 1.188 W. The heat sink area is 0.56 m × 0.26 m with 0.012 m thickness. The surrounding of the heat sink is insulated.

For the real power dissipation, the light power was first measured by the integrating sphere spectrometer, then we used the total input power to deduct the light power to obtain the real heat dissipation amount. The chips used in the present LED lamps are of old types made in 2006, their optical efficiency is relatively low. Therefore although the actual input power is 114 W, the final heat is about 97 W after deducting the light power.

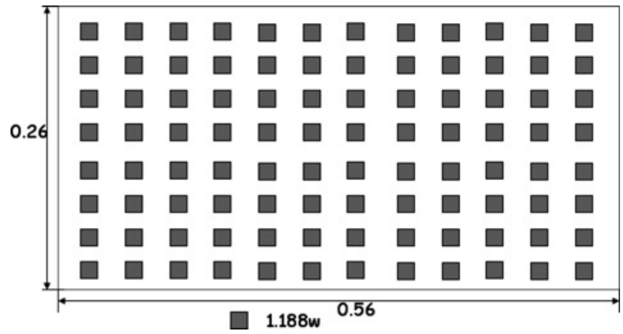

Figure 7 *Structure model for 114-W LED street lamp*

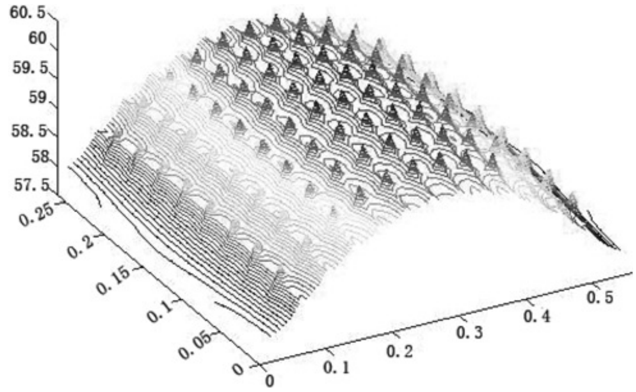

Figure 8 *Chip base temperature of 114-W LED street lamp*

The heat transfer coefficient between the heat sink and the ambient is 1.5 W/m^2 K and the thermal conductivity of the heat sink is 162 W/m K; the ambient temperature is 25.0 °C. It should be noted that in the calculation by using the present model, the heat transfer coefficient could be obtained by empirical equation or by experimental

Table 2 Highest temperature of every heat source row

Row	Highest temperature, °C
Row 1	60.05
Row 2	60.14
Row 3	60.20
Row 4	60.23
Row 5	60.23
Row 6	60.20
Row 7	60.14
Row 8	60.05

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Table 3 Comparison between experimental and calculation results

Method	Ambient temperature, °C	Average temperature of fins and base, °C	Maximum temperature of fins and base, °C
experiment	25.0	60.9	61.7
calculation	25.0	59.0	60.2

measurement based on some temperature values. The excess temperature distribution $\theta_i(x, y, 0)$ of the $z = 0$ surface based on the aforementioned equations can be obtained with the help of code built by us.

The temperature of the heat sink surface contacting with LED chips is shown in Fig. 8 and the highest temperature of every row is given in Table 2. It is found that when the ambient is 25.0 °C, the average temperature of fins and base is 59.0 °C and the maximum temperature of heat sink base that connects with the LED chips is 60.2 °C.

6 Comparison between experimental and calculation results

In order to assess the accuracy of the present model, a comparison between the experimentally measured temperature and calculation data was presented. From Table 3, it can be seen that, in the aforementioned experiments, when temperature of the 114-W high-power LED street lamp is stable, the averaging temperature of the fins and base is 60.9 °C, and the maximum temperature of the fins and base that bond with the LED chips is 61.7 °C with 25.0 °C ambient temperature. For the same case, calculations by using the multiple-chip spreading thermal resistance model show that the averaging temperature of fins and base is 59.0 °C, and the maximum temperature of fins and heat sink base bonded with LED chips is 60.2 °C. The difference of the averaging temperature obtained by the two methods is 3.15%, and the difference of the maximum temperature obtained by the two methods is 2.38%. These demonstrate that the calculation based on the multi-chip thermal resistance is feasible for obtaining the temperature distribution of the heat sink base connected with LED chips. This will greatly facilitate the estimation of LED chip junction temperature in the LED street lamp. Also, it can be used to optimise the LED chip distribution.

7 Summary

In this paper, thermal estimation for high-power LED street lamp based on multi-chip thermal spreading resistance model was presented. The modelling results were validated by experiments for a prototype 114-W LED street lamp. Comparison between the calculation and experimental results demonstrates that simple engineering method can be used for rapid design of thermal management for LED street lamps and other similar high-power LED applications.

8 Acknowledgment

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