Thermal analysis of an 80 W light-emitting diode street lamp

X. Luo, T. Cheng, W. Xiong, Z. Gan and S. Liu

Abstract: Light-emitting diode (LED) street lamps rely heavily on successful thermal management, which strongly affects the optical extraction and the reliability/durability of the LED lamp. A thermal analysis of an 80 W LED street lamp was done. Sixteen thermocouples were used to measure the temperatures at 16 different positions of the street lamp. The results demonstrated that the temperature of the frame and the heat sink of the 80 W LED street lamp remained stable at about 42°C after several hours of lighting at a room temperature of 11°C, and the bulk material resistance of the heat sink could be neglected. Numerical simulation was also used to analyse the temperature distribution of the lamp. The reliability of the numerical model was proven by a comparison of simulation results with the experimental data. Through simulations and the corresponding analyses it was found that the tested 80 W LED street lamp would have poor reliability at an environment temperature of 45°C.

1 Introduction

Theoretically, a light-emitting diode (LED) has many distinct advantages, such as high efficiency, good reliability, long life, variable colour and low power consumption. Recently, LEDs have begun to play an important role in many applications [1]. Typical applications include back lighting for cell phones and other liquid crystal display (LCD) displays, interior and exterior automotive lighting including headlights, large signs and displays, signals and illumination. LEDs will soon be used in general lighting, which consumes about 15% of the total energy all over the world. It is expected that high-power LEDs will be the dominant lighting technology by 2025 [2]. Should the goal come to fruition, then up to 40 GW per year could be saved in the USA alone. It is generally believed that LEDs can be widely used for general lighting in the USA. However, in China, with the government pushing for greater energy savings, LEDs may be used earlier than expected. Chinese authorities estimate that if LEDs dominate the lighting market in 2010, one-third of the present power consumption will be saved, which will greatly ameliorate the energy crisis in China.

One typical general lighting product of LEDs is the LED street lamp, and optical extraction and thermal management are two critical factors that lead to its high performance. In general, most of the electronic power of the street lamp is converted into heat, which greatly reduces the chips' luminosity. In addition, the high junction temperature of LED chips in the lamp shifts the peak wavelength, which changes the colour of the light. Narendran and Gu [3] have experimentally demonstrated that the life of LEDs decreases exponentially with increasing junction temperature. Therefore a low operating temperature is essential for LED chips. Since the market demands that LED street lamps be small yet powerful, there is a contradiction between power density and operating temperature, especially when applications require the LED street lamp to operate at high power to obtain the desired brightness.

In terms of thermal management of the LED street lamp, to the authors' best knowledge, there are no reports or published papers, partially because general lighting, including street lighting, is believed to be a few years away, or perhaps because this field is highly proprietary, as the market for the street lamp is huge. Although there are no reports directly related to the LED street lamp, there have been some studies that introduce the thermal management of high-power LED packaging. Wilcoxon and Cornelius [4] described the thermal management approach for a light engine and presented the results of their finite-element model. The feasibility of the model was proven by the experimental data and was used to assess various design aspects of the light engine to understand their effects on the overall thermal resistance. The results of their finite-element model indicated that the junction temperature of the LEDs in this light engine would be close to their maximum values in a high-temperature environment. However, through the use of exotic materials such as diamond/aluminium composites, LED temperatures can be significantly reduced below the values obtained in this testing. Kim *et al.* [5] investigated the thermal management system for an LED light source in a rear projection TV. Their results showed that decreasing thermal resistance between LEDs and substrate was the most effective way to dissipate heat, and the applicable limit of thermal resistance existed for various heat-dissipating conditions of LEDs. They also suggested that the heat transport system uses red, green and blue LED lights to ensure product quality. Liu *et al.* [6–8] studied a microjet array cooling system for thermal management of a high-power LED

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lighting source. Experimental and numerical investigations were conducted. An infrared thermometer was used to measure the on-line temperature, and thermocouples evaluated the cooling performance of the proposed system. The experimental and numerical results demonstrated that the microjet-based cooling system has good cooling performance. Petroski [9] developed an LED-based spot module heat sink in a free convective cooling system. A cylindrical tube, longitudinal fin heat sink was used to solve the orientation problem of LEDs. Chen *et al.* [10] presented a silicon-based thermoelectric (TE) device for cooling high-power LEDs. The test results showed that their TE device could effectively reduce the operating temperature of high-power LEDs. Acikalin *et al.* [11] used piezoelectric fans to cool LEDs. Their results showed that the fans could reduce the heat source temperature by as much as 37.4°C. Piezoelectric fans have been shown to be a viable solution for the thermal management of electronic components and LEDs.

In this paper, experimental research on an 80 W LED street lamp is described. The temperature of the street lamp was measured by thermocouples. A numerical model for the street lamp was built, and a comparison of the simulation results with the experimental results demonstrated that the numerical model was feasible for the present 80 W LED street lamp. From the simulation results and thermal resistance analysis it was found that the maximum surface temperature of the aluminium base of the lamp is about 80°C, and the junction temperature of the LED chips is nearly close to 120°C at an environment temperature of 45°C.

2 80 W LED street lamp and its thermal path

Fig. 1 is the schematic diagram of the present 80 W LED street lamp. The lamp is mainly composed of three parts: 20 high-power LED modules, a mechanical frame for heat dissipation and supporting LED modules and four slim PCBs for the power input of LEDs. The lamp frame consists of an aluminium base and fins, which are made as one integrated design to save fabrication cost and as well as to decrease thermal resistance. Twenty high-power LED modules are directly bonded to the aluminium base to reduce thermal resistance. They are distributed on the aluminium base in four rows. The modules in the central two rows are 3 W LED packagings, each of which includes three 1 W chips inside. The other two rows consist of 5 W LED modules; each of the 5 W packages includes four chips inside, and they are supplied with 5 W power. Four slim PCBs located on the aluminium base provide power for the four rows of LEDs. When the electronic power is supplied, LEDs generate light and also heat. The heat is

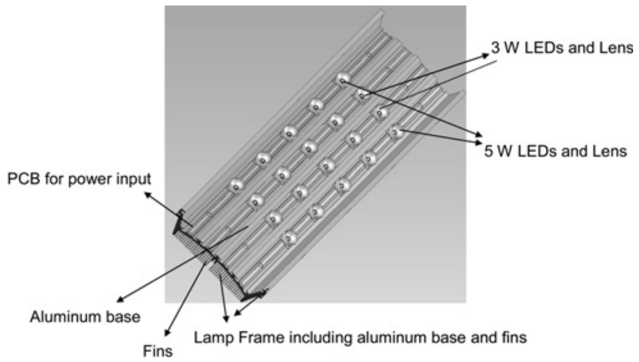

Fig. 1 *Schematic diagram of the 80 W LED street lamp*

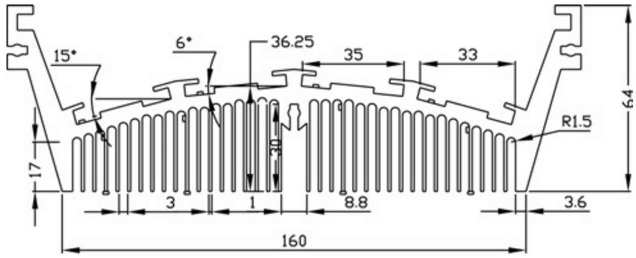

Fig. 2 *Details of heat sink used in the present lamp (all dimensions are in mm)*

dissipated into the environment through the aluminium base and fins. The size of the heat sink for an LED street lamp is shown in Fig. 2 in detail. The length of the heat sink is about 600 mm. The length direction is vertical.

Good optical and thermal performances are the key design elements of a successful LED street lamp. The optical design of the street lamp is to achieve good light quality and make the road bright and comfortable for passengers. However, the optical characteristics of the present LED street lamp will not be discussed in this paper, as its thermal performance and analysis is the main concern.

For the street lamp shown in Fig. 1, low thermal resistance is essential for achieving good thermal and optical performance. The thermal resistance of the 80 W LED street lamp includes five parts, which are illustrated in Fig. 3. The first part is the thermal resistance (R_{cp}) of the packaging of hte high-power LED, which is related to the chip-packaging technology. The second part is the thermal resistance (R_{bd}) of the bonding between the LED substrate and the aluminium base with fins, which is mainly determined by the bonding material and thickness. The third part is the thermal spreading resistance (R_{sp}) between the LEDs and the aluminium base with fins, which is affected by the many geometrical sizes: such as that of the chip substrate, the aluminium base and so on. The fourth part is the bulk material resistance (R_{bk}) of the aluminium base with fins, which is associated with the material and size of the lamp frame. The last part is the thermal convection resistance (R_{conv}) between the fins and the environment, which is influenced by many factors such as fin structure, area and environment wind speed. In Fig. 3, T_j is the maximum junction temperature of the LED chips, T_{c-c} is the maximum temperature in the bonding interface connecting the chip with the aluminium base and T_a is the ambient temperature.

3 Experimental study

3.1 System and temperature measurement

To understand the thermal performance of the 80 W LED street lamp, the temperature distribution of the aluminium

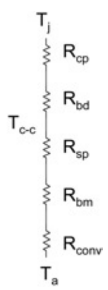

Fig. 3 *Thermal resistance model of the present 80 W LED street lamp*

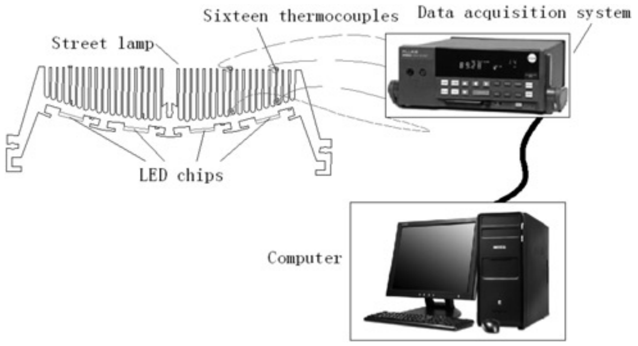

Fig. 4 *Experimental set-up*

base and fins was measured by thermocouples. Fig. 4 shows the experimental set-up. The orientation of the heat sink and the system were set up according to the application condition. The fin base was placed below and the fin tips at the top. The tests were conducted in a natural environment and the 80 W LED street lamp subjected to natural working conditions. The ambient temperature was about 11°C. Sixteen thermocouples were placed at 16 different positions of the aluminium base and fins. The temperature data obtained by the thermocouples were transferred to the data acquisition system and displayed on a PC monitor. The model of the data acquisition system in the experiment was Keithley 2700 multimeter and control unit 7700. It has 20 channels to collect data. Fig. 5 shows the thermocouple distribution on the aluminium base and fins. In Fig. 5*a*, eight thermocouples are located on the fin root, and they are numbered 6, 2, 7, 3, 9, 4, 10 and 5. From Fig. 5*a*, it can be seen that thermocouples 6 and 2 were placed together, with a 5 cm distance along the lamp length direction. In the front view, however, the difference cannot be seen because of the same co-ordinate locations in the other two directions. Similarly, other pairs of thermocouples marked at the same positions, shown in both Fig. 5*a* and *b*, have a 5 cm distance along the lamp length direction. In addition, all these thermocouples were located around the chip modules. The eight thermocouples numbered 17, 11, 16, 13, 14, 10, 19 and 12 were placed on the top part of the fins, as can be seen in Fig. 5*a*. In contrast, they have been moved to the aluminium base at the side of the chip in Fig. 5*b*.

3.2 Accuracy analysis

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 in the thermocouples and error in reading the digital multimeter.

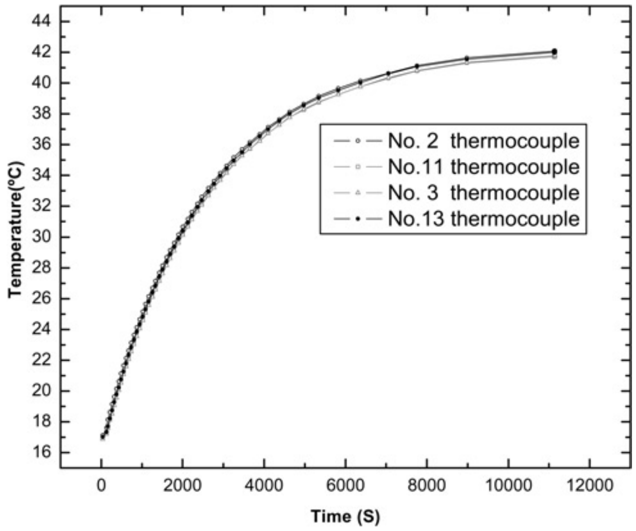

Fig. 6 *Variation of the fin temperature with the operation time for Fig. 5a case*

Standard T-type thermocouples (Cu–CuNi) were used in the experiments. In the temperature range from −30°C to 150°C, the measurement error was about 0.2°C. The data acquisition system had a reading error of 1°C since the cold junctions of the thermocouples used the default set-up supplied by the system, and not the ice bath with constant 0°C. Therefore the total error of the temperature measurement for the experiments was about 1.2°C.

4 Experimental results and analysis

Fig. 6 shows the variation of the fin temperature with the operating time for the case shown in Fig. 5*a*. In the experiments, as already mentioned, the room temperature was about 11°C and there were 16 thermocouples to measure the temperatures at 16 different positions; much data were obtained and it was difficult to display them in one figure synchronously. Thus, the temperatures obtained by the four thermocouples numbered 2, 3, 11 and 13 were used for this description. In Fig. 6, it can be seen that the fin temperature increased as time extended; initially, the fin temperature was nearly the same as the room temperature. After the lamp was activated, its temperature increased. Several hours later, it steadied and the temperature remained stable at nearly 42°C. It can also be noted from Fig. 6 that the temperatures achieved by all thermocouples showed the same trend. The temperature achieved by thermocouple 3 was about 0.6°C lower than the fin tip temperature measured by thermocouple 13, which conflicted with the usual understanding about heat sink temperature distribution. This phenomenon is attributed to the measurement error. In the tests shown in Fig. 6, the temperature

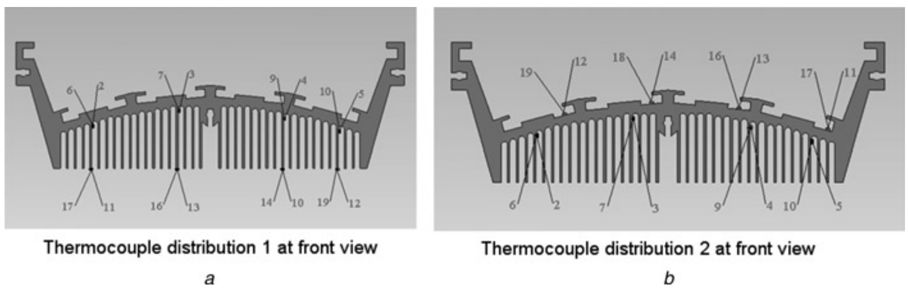

Fig. 5 *Thermocouple distribution at various positions of lamp frame*

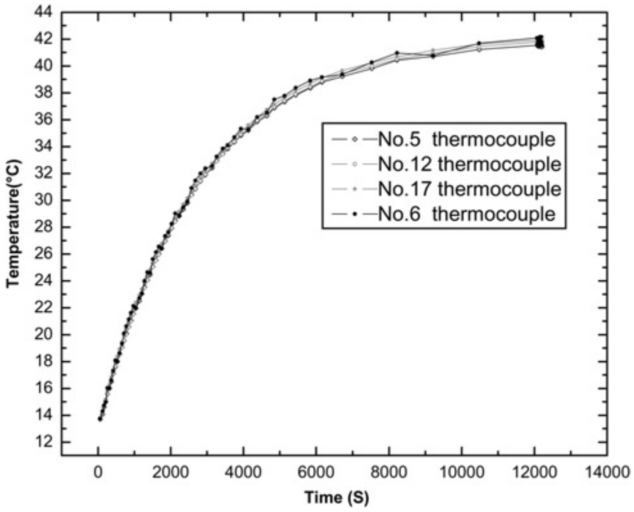

Fig. 7 *Variation of the temperature of the aluminium base and fin with the operation time for Fig. 5b case*

differences among the four thermocouples were very small, less than 1°C; however, the measurement error, as has been described earlier, was about 1.2°C. Therefore the temperature difference between thermocouple 3 and thermocouple 13 does not display the real case. Since the temperature differences among the thermocouples were very small, it can be concluded that the bulk material thermal resistance of the aluminium heat sink was very small and can therefore be neglected.

Fig. 7 shows the variation of the temperature curves for the lamp base and fin with the operation time for the case shown in Fig. 5*b*. The difference between this experiment and that demonstrated in Fig. 6 was that eight thermocouples at the top part of the fins moved to the aluminium base at the side of the chip. From Fig. 7 it can be seen that the temperature change at the aluminium base was the same as those of the other parts of the lamp. The temperature differences among the four thermocouples were also very small; this further demonstrates that the bulk material thermal resistance of the aluminium heat sink was very small and can be neglected.

From the equation $Q = \alpha F \Delta T$, the average heat transfer coefficient of natural convection on the lamp is obtained as follows

$$\alpha = \frac{Q}{F\Delta T} = \frac{70}{1.2 \times (42 - 11)} \mathrm{W/m^2\,K}$$
$$= 1.9\,\mathrm{W/m^2\,K}$$

where α is the average convection heat transfer coefficient and Q the heat; in the present experiments the input power was electrical. Based on our measurements and from standard experience on chips [12], about 13% of the input electrical power is converted into optical energy. The other 87% of the electrical power generates heat. Therefore if the input power of the lamp is 80 W, the heat produced by the lamp is about 70 W, which is mainly dissipated by the fins. F is the heat transfer area of the lamp fins and base, which is about 1.2 m^2. ΔT is the temperature difference between the fin and the environment. Here, the steady average temperature of the fin and base was about 42°C, as shown in Figs. 6 and 7. The environment temperature was about 11°C. Thus, ΔT is about 31 K.

The experiments also show that although the temperature of the aluminium base near the chips was obtained by the thermocouples, the temperature of the aluminium base exactly below the chips could not be measured because of the difficulty in inserting the thermocouple into the bonding material; hence, a numerical simulation is necessary to calculate the temperature for further thermal resistance analysis.

Some important conclusions from the experiments are:

1. At a room temperature of 11°C, the temperature of the frame and heat sink of the 80 W LED street lamp remains stable at about 42°C after several hours of lighting;
2. The temperature of the lamp frame and of the heat sink near the chip modules is nearly the same, and therefore bulk material resistance can be neglected.
3. The temperature of the aluminium base exactly below the chip modules cannot be measured, and a numerical simulation is necessary to solve this problem.

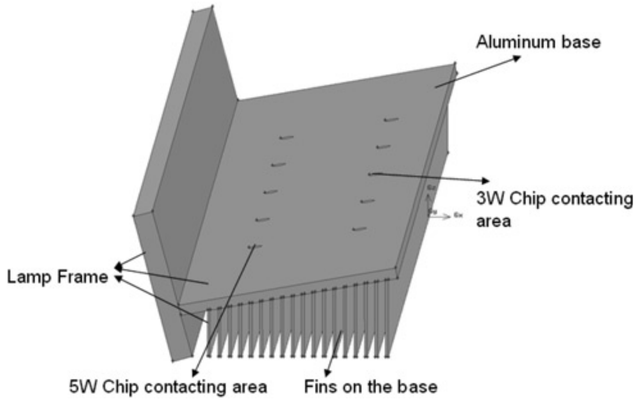

Fig. 8 *Simulation model*

5 Numerical model and feasibility check

Numerical models were built based on the 80 W LED street lamp that was tested, and a typical one is shown in Fig. 8, which illustrates the three-dimensional structure depicted in Figs. 1, 4 and 5. Compared with the real model shown in Figs. 1, 4 and 5, the aluminium base in the numerical model was simplified from the paraboloid as the inclined surface, which was very close to the real paraboloid because of small inclined angle. This was necessary for meshing convenience. In addition, because of the exactly symmetrical design, half of the lamp was modelled to decrease the mesh number. The 5-mm diameter circular contact areas between the 3 W and 5 W modules with the aluminium base are also marked in Fig. 8.

With reference to Fig. 8, the thermal path of the LED lamp is as follows: LED chips produce heat and nearly all the heat is transferred to the aluminium base and fins by thermal conduction; spreading thermal resistance and bulk material resistance also exist in the above process. The heat in the lamp frame, especially in the fins, finally dissipates into the environment by natural convection, which forms the convection thermal resistance. For the above model, the commercial CFD code Fluent 6.2 was used for simulation.

In Fig. 8, the sizes of the lamp are nearly the same as those in the experiments shown in Figs. 1, 4 and 5. The room temperature was about 11°C. To ensure that the conditions were the same as in the experiments, the ten circles where the high-power LED modules are located were subjected to 35 W heat. On the basis of the foregoing experiments, for the fins and the aluminium base exposed to the environment, a convection boundary was adopted in

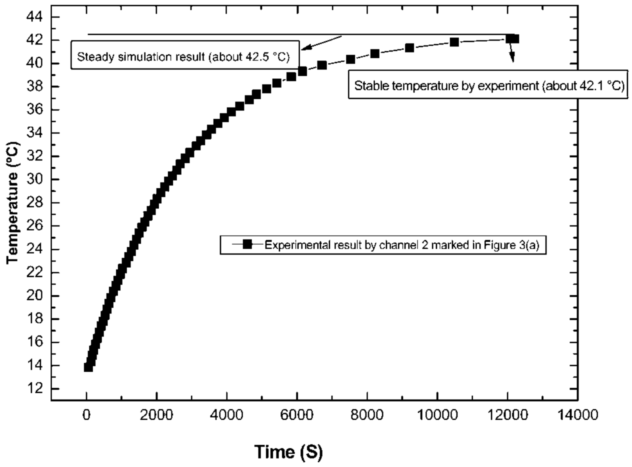

Fig. 9 *Temperature comparison between experiments and simulations*

which the convection heat transfer coefficient was 1.9. A study of the convergence of the grids was conducted before the calculation. The grids were refined until the temperature changed by 0.04%. Finally, 128 778 grids were used in the simulation. The residual control of the energy equation was 1×10^{-9}.

To verify the feasibility of the above model, a comparison between the temperatures in the experiments and simulations is provided, as shown in Fig. 9. It can be seen from Fig. 9 that the steady simulation temperature at the location where thermocouple 2 was placed was 42.5°C, and the steady temperature measured by the thermocouple 2 was 42.1°C. Thus, the temperature difference between the simulation and experimental results measured by thermocouple 2 was 0.4°C. The steady temperature simulation results were also compared with the temperature recorded by other thermocouples at the same positions in the experiment. The results demonstrate that the temperature differences between the simulation and experimental results are small, usually less than 1°C, showing that this model can be used for simulation and further optimisation.

6 Numerical analysis

Fig. 10 shows the simulated temperature distribution of the 80 W LED street lamp. Here, as mentioned in the earlier sections, the simulation conditions were the same as those used in the experiments; the environment temperature was about 285 K. Some information that could not be obtained by the experiments because of the limited measurement points can be gathered from Fig. 10. The temperature at the chip module contact spot was the highest. The maximum temperature in the contact area between the 5 W module and the aluminium base was 320.11 K and in the contact area of the 3 W module it was 319.1 K. The temperature in much of the area around the chips was nearly the same, about 316 K. In the aforementioned experiments, all 16 thermocouples were placed around the LED chip modules, the measured temperature values were nearly the same, and the simulation results shown in Fig. 10 clearly explain and demonstrate the phenomena. It can also be seen that the temperature of the fin and aluminium base at the corner of the lamp is the lowest, 310 K. This low temperature area is very small.

From Fig. 10, the thermal spreading resistance can also be estimated because the total temperature distribution is obtained, which is different from the former experimental measurement. As mentioned before, the maximum total thermal resistance from the chip-bonding material to the ambient can be expressed as

$$R_{\text{total}} = R_{\text{sp}} + R_{\text{bk}} + R_{\text{conv}} \tag{1}$$

where the bulk material resistance R_{bk} has been demonstrated to be very small by the experimental and simulation results and can be neglected; that is $R_{\text{bk}} \simeq 0$. From the simulation results shown in Fig. 10, the convection thermal resistance R_{conv} and R_{total} can be calculated as

$$R_{\text{total}} = \frac{\Delta T}{Q} = \frac{(320.11 - 285)}{35}\ \text{K/W} = 1.003^\circ\text{C/W} \tag{2}$$

$$R_{\text{conv}} = \frac{1}{\alpha F} = \frac{1}{1.9 \times 0.6}\ ^\circ\text{C/W} = 0.877^\circ\text{C/W} \tag{3}$$

Combining (1), (2) and (3), the maximum spreading thermal resistance can be obtained as $R_{\text{sp}} = R_{\text{total}} - R_{\text{conv}} = (1.003 - 0.877)^\circ\text{C/W} = 0.126^\circ\text{C/W}$.

Fig. 11 shows the temperature distribution of the present LED street lamp at an environment temperature of 45°C. It can be seen that the maximum temperature of the chip bonding area on the aluminium base is about 353 K(80°C). Actually, for all the LED products including the present 80 W LED street lamp, the junction temperature of the single LED chip is the main concern, which directly

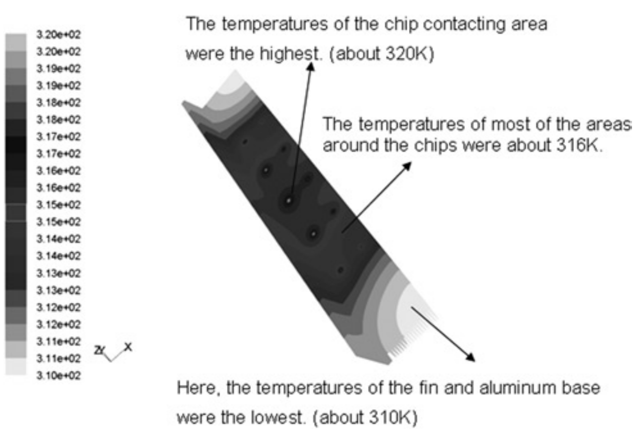

Fig. 10 *Temperature distribution of the 80 W LED street lamp by simulation*

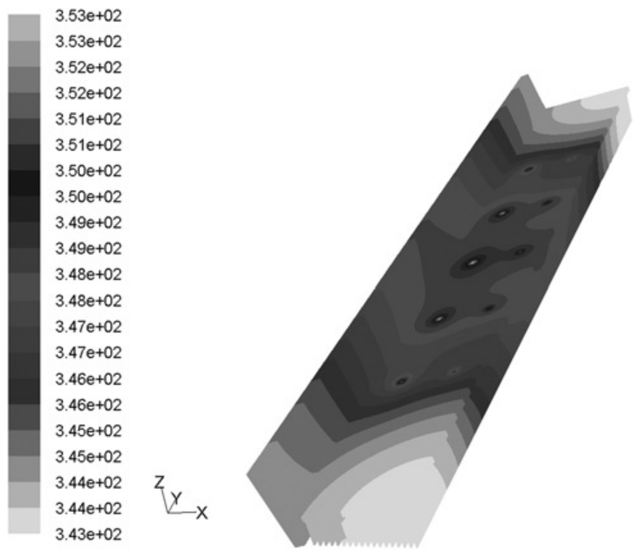

Fig. 11 *Temperature distribution at the environment temperature of 45°C*

determines the life and luminescence efficiency of the LED lamp. From the thermal resistance model shown in Fig. 3, the junction temperature T_j can be calculated. T_{c-c} was the maximum temperature of the chip bonding area on the aluminium base, which can be obtained by the present simulation model, as shown in Fig. 11. R_{cp} was the chip packaging resistance and R_{bd} the bonding material resistance. Therefore the junction temperature of the chips on the present LED lamp can be expressed as

$$T_j = T_{c-c} + QR_{bd} + R_{cp}\, Q_{single\text{-}chip} \quad (4)$$

where Q is the total power of the packaged modules, $Q_{single\text{-}chip}$ was 1 W. Usually, the packaging thermal resistance for the 1 W high-power LED in the market is about 8–14°C/W. The resistance R_{bd} of the chip-bonding material in the experimental lamp was about 5°C/W. Fig. 11 shows that the maximum temperature (T_{c-c}) of the chip-bonding area on the aluminium base was 80°C.

For a 3 W LED module, its packaging thermal resistance R_{cp} was equal to the packaging thermal resistance of the 1 W chip, since it consisted of three 1 W chips. If the packaging thermal resistance for 1 W chip is 12°C/W, R_{cp} would be about 12°C/W. Based on the above analysis, the junction temperature of the single LED chip in the 3 W module of the LED street lamp can be calculated as

$$T_j = (80 + 3 \times 5 + 12)^\circ C = 107^\circ C$$

Using the same calculation method, the junction temperature of the single chip in the 5 W module should be 120°C, which is equal to the critical temperature (120°C) of the LED chip. Therefore it can be concluded that at the environment temperature of 45°C, the present 80 W LED street lamp has poor thermal management, which will correspondingly result in low reliability, short life and low luminescence efficiency.

7 Conclusions

In this paper, the thermal analysis of an 80 W LED street lamp was presented. Sixteen thermocouples were used to measure the temperature points at the aluminium base and fins. The experiments demonstrated that the temperatures near the chip were nearly the same; no obvious temperature difference existed in this area. A numerical model was also proposed based on the experiment. The numerical results were compared with the experimental results to ensure the feasibility of the numerical model. The numerical results of the thermal resistance analysis showed that at an environment temperature of 45°C, the maximum junction temperature of the LED chips on the present 80 W LED street lamp would be equal to the critical temperature 120°C, which leads to poor reliability and lower life and optical efficiency of the LED street lamp.

8 Acknowledgments

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