Thermal design for the high-power LED lamp

Tian Xiaogai(田晓改)†, Chen Wei(陈伟), and Zhang Jiyong(张继勇)

NVC Lighting Technology Corporation Research & Development Center (Shanghai), Shanghai 201112, China

Abstract: This paper summarizes different kinds of heat sinks on the market for high power LED lamps. Analysis is made on the thermal model of LED, PCB and heat sink separately with a simplified mode provided. Two examples of simulation are illustrated as a demonstration for the thermal simulation as guidance for LED lamp design.

Key words: high power LED; LED lamp; lamp body (heat sink); thermal simulation

DOI: 10.1088/1674-4926/32/1/014009 **EEACC:** 2520

1. Introduction

High-power LEDs are becoming popular in recent years. Normally, about twenty percent of power input to LED is converted into the light energy and the left, eighty percent of energy converted into heat, so it is important to dissipate the generated heat. The higher the power, the more the heat is produced. If the heat could not be dissipated immediately, it will concentrate on the tiny LED chip and cause the junction temperature of the chip to rise to a harmful level. Narendran and Gu[1] have experimentally demonstrated that the life of LED decreases with increasing junction temperature in an exponential manner. Therefore, low junction temperature is essential for LED performance, which is a distinguishing feature of LED lamp versus traditional lighting. Since the market requires that LEDs have high power and packaging density, it poses a contradiction between the power density and the operation temperature, especially when LEDs are operated at a normal or higher driver current to obtain the desired lumen output. So heat dissipation becomes a key issue in the application of high-power LED.

2. Current cooling means for LED lamp

In order to design an LED lamp with a high-effect cooling ability, a suitable design will be essential. Usually people use the heat sink with different shapes to dissipate heat, so the heat sink is a major part in lamp design. Usually, there are two ways for the cooling of the heat sink: passive cooling and active cooling. However, the fan for active cooling will cause some problems, such as noise and short lifetime, thus normally active cooling is not suitable for LED lamps. The heat is dissipated mainly by natural convection of the lighting body itself. The design of the lighting body with the function of heat sink is playing an important role in LED product today.

There are many factors we need to consider in order to design an LED lamp with a good cooling system, such as structure, shape of the lamp, and material characteristic. From the way of molding, LED lamps can be classified into several kinds as follows.

2.1. Extruding forming- lamp body of aluminum product

The material used for extruding forming usually has high thermal conductivity. The advantages of the extruding forming are a simple process and high productivity. However, the adjustment of the shape is poor, which is restricted by the machining property, and the cost of machining is high. So it isn't suitable for batch production.

2.2. Casting molding-lamp body of aluminum product

Now most casting molding lighting bodies are made of the material, ADC12, whose thermal conductivity is lower than other types of aluminum. Although the initial cost (mode design and manufacturing) is higher, the average cost is comparatively lower to other molding methods. The most important advantage is that its shape adjustment capability is very strong which allows more accurate manufacturing.

2.3. Plug blades forming-lamp body of aluminum product

For this forming way, the fins of the heat sink are all plugged into the body base, which save the material and cost, with the advantage of simple processing and high throughput.

Figure 1 is the relationship curve of thermal resistance of heat sink with the lighting efficiency. From the curve, we know that a better design of heat sink (lamp body) will result in a higher light efficiency. The data come from a simple simulation whose thermal model is composed of three LED with a total power of 3 W and one heat sink, whose thermal resistance changes when its dimensions change.

3. Thermal simulation models for the LED lamp

3.1. Theory of simulation

The thermal simulation is assumed by the software CFD. The solution procedures in CFD are based on CFD technique. CFD is concerned with the numerical simulation of fluid flow, heat transfer and related processes such as radiation. The essential equations used in the simulation are below.

† Corresponding author. Email: tianxiaogai@sina.com
Received 20 September 2010

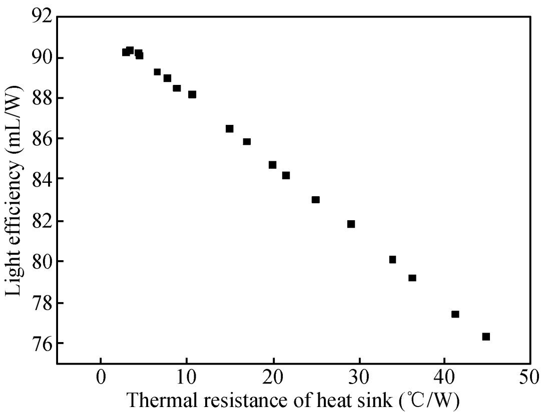

Fig. 1. Relationship of thermal resistance of heat sink with the light efficiency.

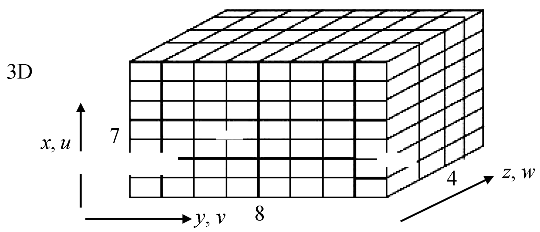

Fig. 2. Simple figure of grid dissipation.

(1) Mass conservation equation[2]:

$$\frac{\partial \rho u}{\partial x}+\frac{\partial \rho v}{\partial y}+\frac{\partial \rho w}{\partial z}+\frac{\partial \rho}{\partial t}=0. \tag{1}$$

(2) Momentum conservation equations in the three coordinate directions[2]:

$$\rho\frac{D\boldsymbol{V}}{Dt}=\rho\boldsymbol{B}-\nabla P+\mu\nabla^2\boldsymbol{V}. \tag{2}$$

(3) Thermal energy conservation equation[2]:

$$\dot{Q}=\rho AV\left[u_2-u_1+\left(\frac{P_2}{\rho}+\frac{V_2^2}{2}+gz_2\right)-\left(\frac{P_1}{\rho}+\frac{V_1^2}{2}+gz_1\right)\right]. \tag{3}$$

The conservation equations and their associated boundary conditions do not have a general analytical solution. CFD provides the means of numerical integration. The conservation equations are discretized by sub-division of the domain of integration into a set of non-overlapping, contiguous finite volumes over each of which the conservation equations are expressed in algebraic form. These finite volumes are referred to as grid cells, control cells or quite simply as cells. The discretization results in a set of algebraic equations, each of which relates the value of a variable in a cell to its value in the nearest-neighbor cells. The simple figure for grid dissipation is shown in Fig. 2.

3.2. Thermal model of the LED lamp in CFD

From Fig. 3 we see that there are five main parts for a LED lamp system. Following the direction of heat flowing, there are

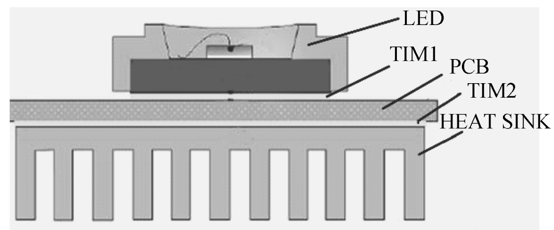

Fig. 3. Main heat dissipation structure for LED.

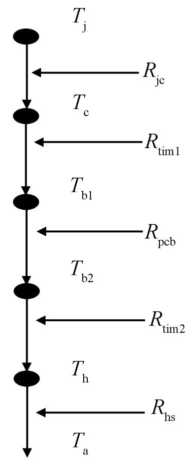

Fig. 4. Main heat resistance structure for LED.

LED, thermal interface material 1 (TIM1) between LED and PCB, PCB, thermal interface material 2 (TIM2) between PCB and heat sink which equivalent to the lighting body. Simultaneously, these parts cause five main thermal resistances, as shown in Fig. 4.

R_{jc} is the thermal resistance from the junction of die to the case. R_{tim1} is the thermal resistance of the thermal interface material 1. R_{pcb} is the thermal resistance of PCB. R_{tim2} is the thermal resistance of the thermal interface material 2. R_{hs} is the thermal resistance of the heat sink, which represent for the cooling ability of the lighting body. For the five different thermal resistances, thermal model of R_{tim1} and R_{tim2} are easy to be established if we could get the accurate data. More attention should be paid to establish the model of LED, PCB and lighting body before simulation.

3.2.1. Thermal model of LED

There are two ways to establish the LED model: one is the accurate model, and the other is the simplified model. If we know the detailed structure, dimensions and thermal property of the LED, it is better and more accurate way to establish a detailed model. But usually it is hard to get right and complete parameter data. At this condition we need to seek simple way to assume the thermal model of LED.

3.2.1.1. Accurate model of LED

The accurate model of LED is shown in Fig. 5.

3.2.1.2. Simplified model of LED

The LED model is replaced by a compact component with two resistances, one is R_A, and the other is R_{JC}, as shown in Fig. 6. R_A is the resistance between the die junction and the top. R_{JC} is the resistance between the die junction and the PCB. We

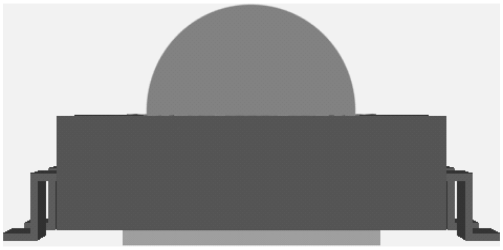

Fig. 5. Accurate model of LED.

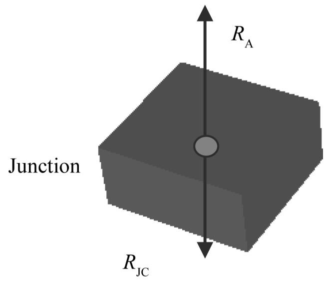

Fig. 6. Model of two resistances.

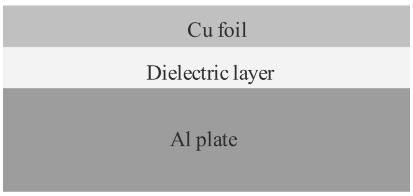

Fig. 7. Structure of MCPCB.

Table 1. Property parameter of different structures for MCPCB.

Parameter	Thickness	Conductivity
Cu foil	1 oz	400 W/(m·K)
Dielectric layer, MP	75 μm	1.3 W/(m·K)
Al plate	1.5 mm	150 W/(m·K)

know that most of the heat regenerated is dissipated through the bottom heat sink of LED, and much less through the top case and surroundings case. So we assume that R_A and R_{JC} are just the two resistances, R_A is much bigger than R_{JC} and the resistance is ∞ between the die junction and the surroundings case.

3.2.2. Thermal model of PCB

There are three kinds of PCB, ordinary double-sided bonded copper (FR4), aluminum-based bonded copper (MCPCB) and flexible film PCB pasted on the aluminum board, which are used in high-power LED cooling currently. Now we take MCPCB as an example to show how to establish its thermal model.

Seen from Fig. 7 and Table 1, the thermal resistance of PCB is consisted of three parts, Cu foil, dielectric layer and aluminum plate. With higher thermal conductivity and thinner thickness, the thermal resistance of Cu foil could be ignored. So we just need to establish two layer of thermal model, or just one simplified thermal model. For simplified model, we could get effective thermal conductivity λ_{eff} at different directions

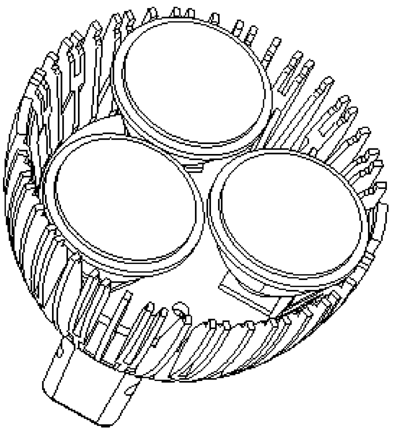

Fig. 8. 3D mechanical structure of LED lamp.

x, y and z, according to Eq. (1)[3].

$$\frac{A\delta_{overall}}{\lambda_{eff}} = \frac{A\delta_1}{\lambda_1} + \frac{A\delta_2}{\lambda_2}. \quad (4)$$

3.2.3. Thermal model of lamp body

When we assume the thermal model of lighting body, we need to simplify its mechanical structure and remove some parts where have little impedance on the whole thermal system, such as the screws. According to Eq. (5)[3], we know that the basic principle of simplification is to ensure the area for heat dissipated A, and the heat transfer coefficient h are essentially same as the mechanical model itself. And then we will get a simulation result approaching to the real data.

$$Q = hA(T - T_\infty), \quad (5)$$

where Q is the heat dissipated for the lighting body (heat sink), W; h is the heat transfer coefficient, W/(m^2·K); A is the area for heat dissipated, m^2; T is the temperature of heat sink, K; and T_∞ is the temperature of surrounding air, K.

4. Examples of thermal simulations for LED lamp

We could see the essential mechanical structure from Fig. 8. According to the method mentioned above we establish one simplified thermal model. Given first is the simplification of the LED and the PCB, and then is the assumption of the lamp body following Eqs. (4) and (5).

4.1. Thermal simulation result for the closed and the open lamp body

For such LED lamp products on the market, they are mainly divided into two categories: one is the products whose lamp body is closed, and the other is open, such as Fig. 8. From the point of view of heat dissipation, convection will be more intense for the open lamp body, whose heat transfer coefficient h will be higher and therefore more heat will be dissipated. Table 1 is the simulation results under these two conditions with test results for the open lighting body as comparison. The input current is 340 mA, and the input voltage is 11.5 V for both

Table 2. Simulation result and test result comparison.

Condition	LED 1 T_J (℃)	LED 2 T_J (℃)	LED 3 T_J (℃)
Test result of open body	76	77	77
Simulation-open lamp body	78.6	79.4	79.3
Simulation-closed lamp body	82.2	83	83.8

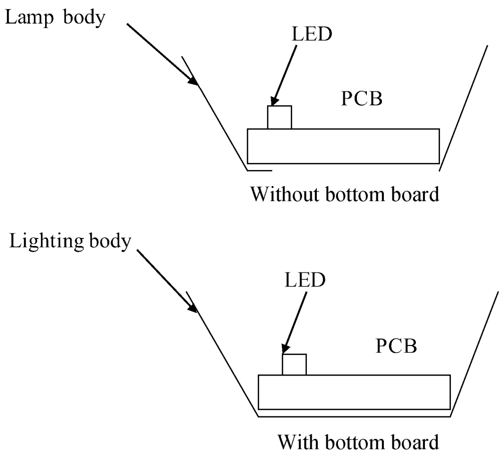

Fig. 9. Figure of two kinds of lamp body.

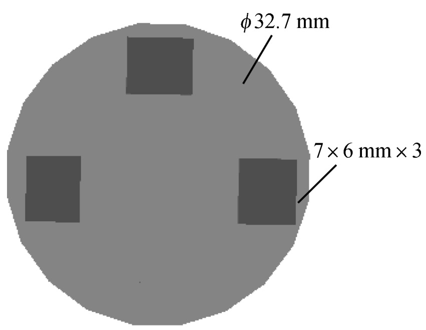

Fig. 10. Thermal model of LEDs on PCB.

simulation and test situation. All of the environment temperature is 24 ℃. The test result is about 2 ℃ less than simulation result, because we ignore some factors during simulation, seen from Table 2. From the simulation result comparison, we know that the junction temperature of open lighting body is about 4 K lower than the closed body at the same simulation condition.

4.2. Thermal simulation for the lamp body with and without the bottom board

Another classification is that of whether the lamp body and PCB are in contact with bottom board. Whether the lamp body with a bottom board will dissipate more heat is influenced by the location of LED on the PCB. Figure 9 shows the figure of two kinds of lamp body, showing the condition that we have the chance to remove the bottom board. Figure 10 is the thermal models of PCB, from which we know that the LEDs are close to the edge of PCB. We give the simulation at these two conditions. From Fig. 11 the temperature profile of PCB for the two kinds of lamp body, we find that the temperature profiles are merely same for these two conditions, and the temperature difference is less than 1 ℃. So we can take out the bottom board

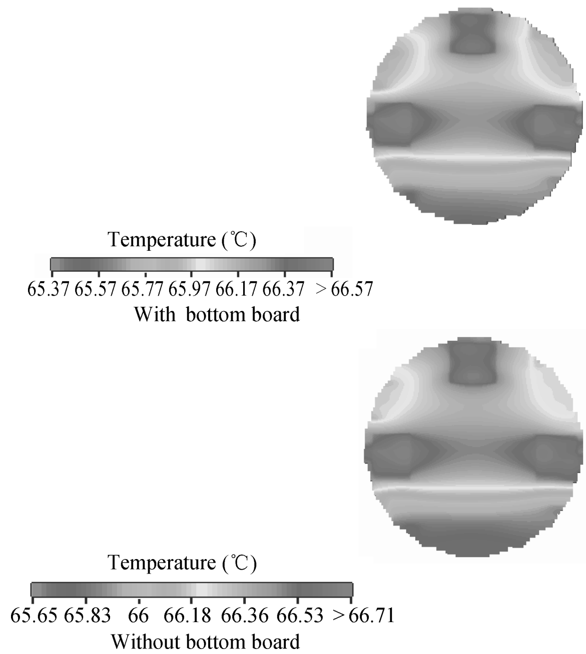

Fig. 11. Temperature profile of PCB for the two kinds of lamp body.

when the placement of LEDs is near the edge of the PCB, which decreases the weight of the lamp body and is more important to cut down the cost of the lamp body.

5. Conclusions

Thermal simulation is essential and important for LED product design. Through the simulation we could forecast the approximate temperature of LED and decide which proposal is appropriate for the heat dissipation. From this article we know how to simplify a mechanical model to a thermal simulation model, including LED model, PCB model and the lighting body model. The two simulation example tells us that the junction temperature of open lamp body is about 4 K lower than the closed body at the same simulation condition. The temperature profiles of LEDs are merely same, the difference less than 1 ℃ when LEDs are near the edge of the PCB.

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