Effect of Heat Sink Structure on Cooling Performance of LED Bulb

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Abstract

This paper describes the effects of various parameters on the temperature of the LED device to optimize the heat sink structure of LED light bulb, and a design guideline is shown. Although the original efficiency and life of the LED device is excellent, the performance cannot be obtained due to the local temperature rise of LED element and the surrounding polymer molding material. Therefore, heat transfer analysis considering the heat convection and radiation was carried out systematically using finite element method by changing parameters of the heat sink shape. The result has shown that open type structure has advantage, and the proper design guideline for the structure of shape was obtained. Furthermore, an experimental model was prototyped, then the temperature distribution was measured, consequently it has been verified that the analysis results were well consistent with the empirical data.

Keywords: light emitting diode bulb, heat sink, heat transfer, finite element method, temperature distribution

1 Introduction

In recent years, LEDs have been used for traffic signals, lighting in road tunnel and lamp for home due to their long life and high efficiency, further the applications to the head lamp and tail lamp of automobile has been started as well [1]-[2]. However, the LEDs are point heat sources, thus the potential efficiency cannot be obtained, because the local temperature of the polymer molding materials [3], peripheral devices and LED element itself increases when LEDs are assembled to LED bulb, namely the heat transfer design issues have been preserved. For example, it is known that the luminous efficiency may decrease 5-8% when the temperature rises 10˚C, life is halved for every 10˚C rise in temperature, furthermore, the specific issues of LED have been reported, such as thermal degradation of the material of the feeding unit and the mounting part of LED element, and the increase of failure rate due to insulation failure and fatigue failure resulting from thermal stress [2], [4], [5].

A group of the authors has reported on the thermal design of the LED lamp using simulation [6]. However, only convection heat transfer was considered due to the use of simplified geometrical models in the analysis. Further the verification of the theoretical analysis has not been conducted. Therefore, in the present study, both convection and radiation were considered in the heat transfer analysis of LED heat sink using finer geometrical models, then the result was verified by measuring the temperature distribution of a practical proto-typed model.

2Analysis methods and conditions

2.1 Analysis method

Three dimensional unsteady-state heat transfer analysis using the finite element method [7] was carried out considering heat convection and radiation and temperature distribution was obtained. Basic model of the LED heat sink is shown in **Fig. 1**. As shown in **Table 1**, three levels of condition were set in each of the eight parameters; the presence or absence of the outer cylinder, the number of heat radiation fins, the height of the heat radiation fin, the thickness of the fin, the thickness of the upper plate, the material, the internal temperature of the outer cylinder, and the number of LED tips, then the parameters were allocated in the L_{18} orthogonal table using Design of Experiments (DOE) as shown in **Table 2**. The influence of each parameter was quantified by creating a regression equation.

2.2 Analysis conditions

The heat generation of the LED bulb was fixed to 6 W as a whole, that is 2 W per element when the number of LED elements are three, and 1 W per element for six LED elements, the influence of the number of LED elements on the maximum temperature was investigated, Assuming a resin molding, the shape of the LED element has a disk shape with a height of 2mm and a diameter of 4mm. The diameter of the mounting substrate of LED element was fixed at 60mm. In addition, the ambient temperature was set at 20˚C, and the heat transfer coefficient was applied to 5 W/m^{2}K to be used in calm condition of a typical convection, and relative emissivity was 0.4. Further, assuming the heat build-up in the outer cylinder, the temperature in the outer cylinder was varied in the range from 20 to 45˚C. As the material of the radiation fin, aluminum alloy, which can be easily formed by die-casting or stamping, and has reasonable cost, was selected and compared with copper and stainless steel. **Table 3** shows the material properties used. With respect to the heat dissipation structure, the number of fins, the height of fin, the thickness of fin, were varied in the practical range, and also examined the effect of the presence or absence of the outer cylinder, that is, open type and closed type.

Table 1 Calculation condition for the analysis

Parameter	Level		
	1	2	3
with/withoutcylinder	with	with	without
Number of fins	3	12	24
Hight of fins [mm]	10.5	15.5	20.5
Thickness of fins [mm]	1	2	3
Thickness of substrate [mm]	1	2	3
Materials	SUS	Al	Cu
Inner temparature [℃]	22	30	45
Number of LED chips	1	3	6

Table 2 L_{18} orthogonal table

No.	Cylinder	Number of fin	Hight of fin	Thickness of fin	Thickness of substrate	Material	Inner temp.	Number of chips
1	With	3	10.5	1	1	SUS	22	1
2	With	3	15.5	2	2	Al	30	3
3	With	3	20.5	3	3	Cu	45	6
4	With	12	10.5	1	2	Al	45	6
5	With	12	15.5	2	3	Cu	22	1
6	With	12	20.5	3	1	SUS	30	3
7	With	24	10.5	1	1	Cu	30	6
8	With	24	15.5	2	2	SUS	45	1
9	Without	24	20.5	3	3	Al	22	3
10	Without	3	10.5	1	3	Al	30	1
11	Without	3	15.5	2	1	Cu	45	3
12	Without	3	20.5	3	2	SUS	22	6
13	Without	12	10.5	1	3	SUS	45	3
14	Without	12	15.5	2	1	Al	22	6
15	Without	12	20.5	3	2	Cu	30	1
16	Without	24	10.5	1	2	Cu	22	3
17	Without	24	15.5	2	3	SUS	30	6
18	Without	24	20.5	3	1	Al	45	1

Table 3 Property of materials

Property	SUS	Al	Cu
Density[kg/㎥]	7750	2770	8300
Thermal conductivity [W/m℃]	15.1	149	410
Specific heat[J/kg・℃]	480	875	385

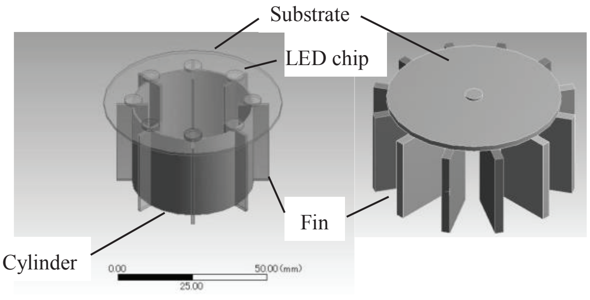

Fig. 1 Basic models used for analysis

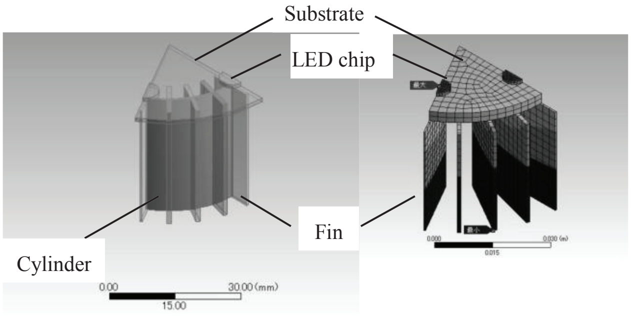

Fig. 2 Examples of calculation model

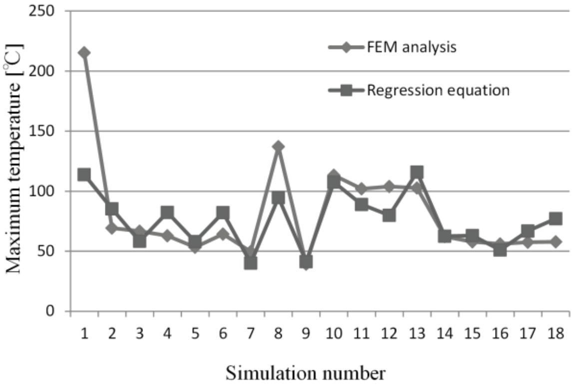

Fig. 3 Comparison between the results of regression analysis and finite element method analysis

3 Results and Discussion

The 18 conditions allocated into orthogonal table were analyzed, and then multiple regression analysis on the effects of the parameters on the maximum temperature was conducted using the temperature distribution obtained in the case where convection and radiation were considered.

The obtained regression equation is shown below.

$$T_{max}=147.2-6.34Q_a-1.29Q_b-1.81Q_c+0.1Q_d -1.42Q_e-16.14Q_f+0.80Q_g-4.14Q_h$$

where, T_{max} : maximum temperature, Q_a : with or without cylinder, Q_b : the number of fins, Q_c : the height of fins, Q_d : the thickness of fins, Q_e : the thickness of substrate, Q_f : material, Q_g : inner temperature, Q_h : the number of LED chips .

In **Fig. 4**, influence factor of each parameter on T_{max} in the range of present condition, namely the value multiplied the coefficient of the above equation Q_a by the range of each parameter (the range between level 1 to level 3) Δx_i , is shown.

The impact factor on the maximum temperature T_{max} is greater in the order of the material of fin, the number of fins, the number of LED chips, the height of fin and the thickness of the substrate, that is the order of cooling effect in the ranges of present condition.

Using the regression equation and the influence factor, the best model showing the lowest T_{max}, the worst model showing the highest T_{max} and the reasonable model considering manufacturing cost and ease of maintenance explained later, were selected.

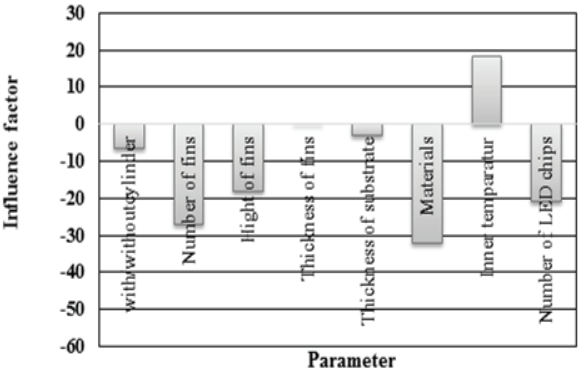

Fig. 4 Influence factor of each parameter on the maximum temperature (heat transfer and radiation)

The parameters used are shown in **Table 4** and the created models are shown in **Fig. 5**, **Fig. 6** and **Fig. 7**. Regarding the best model, in which the material of fin is copper with the highest heat conductivity, and six LED chips are placed on the substrate, and the 24 fins have the height of 15mm. Further the structure has cylinder, that is cylinder type. The calculated result by FEM shows a maximum temperature T_{max} of 38˚C. In practical case, the inner temperature becomes almost same temperature as the cylinder, therefore re-calculation was conducted for the cylinder type. The result has shown that the open type which prevent the increase of inner temperature is better than the cylinder type.

Table 4 Parameter and calculated result of each model

Parameter	Best	Better	Worst
with/withoutcylinder	with	with	without
Number of fins	3	12	24
Hight of fins [mm]	20.5	15.5	10.5
Thickness of fins [mm]	2	2	2
Thickness of substrate [mm]	3	2	1
Materials	Cu	Al	SUS
Inner temparature [℃]	22	30	45
Number of LED chips	6	3	1
Maximum temperature [℃]	38.3	54.2	242.3
Minimum temperature [℃]	37.8	50.9	84.5

The worst model shown in **Fig. 6** has smaller area of fin, and has only one LED chip placed at the center of the substrate, made of austenitic stainless steel with lower thermal conductivity. The maximum temperature T_{max} in the case was 242˚C. Consequently, the difference between the best and worst models was found to be greater than 200˚C.

The above mentioned best model is appropriate only for cooling effect, in practical application, manufacturing method, production cost, ease of maintenance and design properties.

The reasonable model similar to the best model is shown in **Fig.7**.In this case the maximum temperature is 54˚C. The model has a little simpler fin structure made of aluminum and has the cylinder type as well as the best model. It is suggested that the practicality of the model is high although the maximum temperature is a little higher than that of the best model.

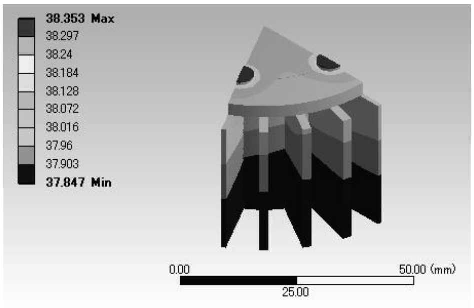

Fig. 5 Best model

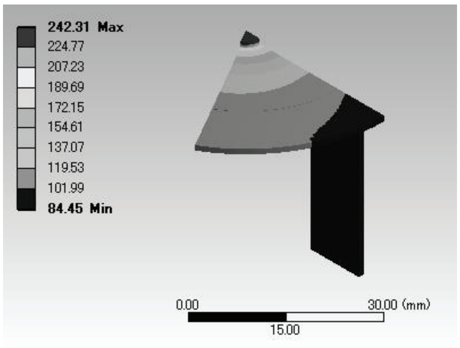

Fig. 6 Worst model

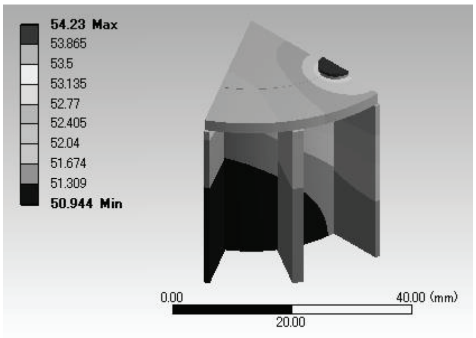

Fig. 7 Reasonable model

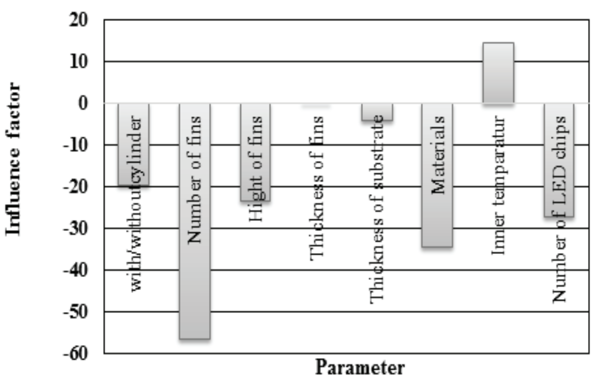

Fig. 8 Influence factor of each parameter on the maximum temperature (without radiation)

4. Experimental method and result

4.1 Experimental method and condition

An experimental model was prototyped as shown in **Fig. 9**. Small resistant chips were placed with adhesive on the substrate plate as heater, then heat input was supplied using a direct current power supply. Temperatures at the center of the substrate plate and the end of a fin were measured by a thin film type thermo couple, further the temperature distribution of the model was observed by a thermo-viewer (CHINO; CPA-0170A), setting the relative emissivity ε to 0.71. On other hand, calculation was conducted at the above experimental condition.

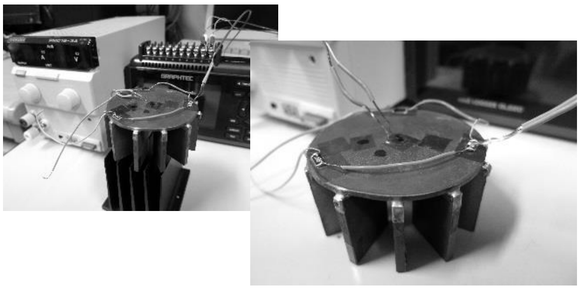

Fig. 9 A model proto-typed for experiment

Table 5 Comparison between measured and calculated temperature

	Position	
	Center of substrate plate	End of fin
Measured with thermo-couple	58.5˚C	55.3˚C
Measured with thermo-viewer	58.5˚C	55.0˚C
Calculated by FEM	56.5˚C	53.5˚C

4.2 Experimental result and discussion

The empirical and calculated results are shown in **Table 5**. A set of empirical values was consistent well with the calculated values, although the experiment was conducted only for one construction due to difficulty in manufacturing some models, and the empirical values showed higher by approximately two centigrade. Therefore, it is suggested that the obtained results in this paper is verified in a range of the present condition.

5. Conclusion

With regard to a LED bulb with a diameter of 60mm and a power of 6 watt, the effect of the heat dissipation structure was analyzed by the FEM method in order to minimize the maximum temperature which affect electric efficiency and life, and the following results were obtained.

(1) It was found that the influence factor on the maximum temperature of the LED chips was greater in the order of the presence or absence of outer cylinder, the number of fins, and the number of LED tips, and so forth on the maximum temperature of the LED chips

(2) It was confirmed that the open type structure without outer cylinder was effective to prevent the increase of inner temperature.

(3) Within the studied condition, the worst structure showed a lowest max. temperature of 186˚C, however the best model can decrease the max. temperature to 38˚C.

(4) Using the regression equation obtained by the FEM calculation results, the maximum temperature can be estimated without the change of CAD diagram and FEM analysis in a range of the present condition.

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