Optimizing Structure of LED Light Bulb for Heat Transfer

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Abstract. In this paper, in order to optimize the heat transfer structure of LED light bulb, the effects of various parameters on the temperature of the LED device were systematically analyzed, and a design guideline was shown. Although LED device has become popular due to its high-efficiency and long life, the design issues on the heat transfer structure of LED light bulbs has still remained. Because the original efficiency and life of the LED device can not be obtained due to the local temperature rise of LED element and the surrounding polymer molding material. Therefore, heat transfer analysis by finite element method was conducted systematically by changing parameters such as the shape, number and thickness of the radiating fin of the LED. As a result, advantage of open type structure was shown, and the proper design guidance for the structure of the fin shape was obtained.

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 rise 10°C, life is halved for every for every 1°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].

It is considered, in general as well as electronic equipment, that the heat transfer problems in the structures can be qualitatively solved by reducing the ambient temperature and the increase in the thermal conductivity and the target radiation area. However, the compression of development period...
and cost is difficult by the conventional processes, such as prototyping and performance evaluation test, since there are many parameters. Therefore, it is considered to be effective to utilize Computer Aided Engineering (CAE), which has been frequently used in automotive industry, in the development of the LED lighting. However, there is little report on the thermal design of the LED lamp using the simulation. A group of the anthers has reported that the effect of heat dissipation area is greater than that of cross-sectional area of heat conduction as for the heat dissipation structure of LED bulb, and that an open structure will be effective to prevent the heat from being trapped inside the bulb [6].

In the present work, focusing mainly on the shape of heat radiation fin, the number of the LED elements, the thickness of parts, the presence or absence of the outer cylinder, a thermal analysis by finite element method was performed, and the guidelines for the design of the structure was obtained.

2. Analysis methods and conditions.

2.1. Analysis method

Eight parameters were allocated to 18 cases using Design of experiments (DOE), then three dimensional steady-state heat transfer analysis using the finite element method [7]. From the obtained temperature distribution, multiple regression analysis on the effects of the parameters on the maximum temperature was carried out; the influence of each parameter was quantified by creating a regression equation. First, as shown in Table 1, more specifically, 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 fin, 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 tip. Then, as shown in the table of condition in Fig. 2, 18 conditions were allocated using DOE. Based on these cases, axially symmetrical part models for analysis were created using 3 dimensional CAD. An example of the entire shape model is shown in Fig. 1. Fig. 2 shows an example of the axially symmetrical part model.

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 investigate, 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/m²K] to be used in calm condition of a typical convection. 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, Aluminium 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.

| Parameter                        | Level         |
|----------------------------------|---------------|
| with/without cylinder            | with          |
| the number of fin                | 3             |
| the height of fin [mm]           | 5             |
| the thickness of fin [mm]        | 1             |
| the thickness of substrate [mm]  | 1             |
| material                         | Type 304     |
| inner temperature [°C]           | 20            |
| the number of LED                | 1             |
Table 2 18L orthogonal table

| No. | with/without cylinder | the number of fin | the thickness of fin [mm] | the thickness of substrate [mm] | material | inner temperature [°C] | the number of LED |
|-----|----------------------|------------------|--------------------------|-------------------------------|----------|------------------------|------------------|
| 1   | with                 | 3                | 10.5                     | 1                            | Type 304 | 1                      | 22               | 1                |
| 2   | with                 | 1                | 15.5                     | 2                            | Al       | 2                      | 30               | 3                |
| 3   | with                 | 1                | 20.5                     | 3                            | Cu       | 3                      | 45               | 6                |
| 4   | with                 | 12               | 10.5                     | 1                            | Al       | 2                      | 45               | 6                |
| 5   | with                 | 1                | 15.5                     | 2                            | Cu       | 3                      | 22               | 1                |
| 6   | with                 | 1                | 20.5                     | 3                            | Type 304 | 1                      | 30               | 3                |
| 7   | with                 | 1                | 10.5                     | 1                            | Cu       | 3                      | 30               | 6                |
| 8   | with                 | 1                | 15.5                     | 2                            | Type 304 | 1                      | 45               | 1                |
| 9   | with                 | 1                | 20.5                     | 3                            | Al       | 2                      | 22               | 3                |
| 10  | with/without         | 0                | 10.5                     | 1                            | Al       | 2                      | 30               | 3                |
| 11  | with/without         | 0                | 15.5                     | 3                            | Cu       | 3                      | 45               | 3                |
| 12  | with/without         | 0                | 20.5                     | 3                            | Type 304 | 1                      | 22               | 6                |
| 13  | with/without         | 0                | 15.5                     | 1                            | Type 304 | 1                      | 45               | 3                |
| 14  | with/without         | 0                | 20.5                     | 2                            | Al       | 2                      | 22               | 6                |
| 15  | with/without         | 0                | 15.5                     | 2                            | Cu       | 3                      | 30               | 1                |
| 16  | with/without         | 0                | 10.5                     | 2                            | Cu       | 3                      | 22               | 3                |
| 17  | with/without         | 0                | 15.5                     | 3                            | Type 304 | 1                      | 30               | 6                |
| 18  | with/without         | 0                | 20.5                     | 3                            | Al       | 2                      | 45               | 1                |

Table 3 Property of materials

| material | Type 304 | Cu | Al |
|----------|----------|----|----|
| density [kg/m³] | 7930 | 8880 | 2693 |
| efficiency of heat transfer [W/°C] | 16.7 | 398 | 235 |
| specific heat [J/kg °C] | 590 | 380 | 860 |
3. Analysis of 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. The obtained regression equation is shown below.

\[ T_{\text{max}} = 190.08 + 3.27Q_a - 1.95Q_b - 2.78Q_c + 0Q_d - 9.18Q_e - 15.39Q_f + 0.617Q_g - 6.17Q_h \]

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

In Fig 3, impact factor of each parameter on \( T_{\text{max}} \) 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) \( \Delta x_i \), is shown.

![Fig.3 Comparison between equation of regression and result of the finite element method](image)

![Fig.4 Influence on maximum temperature degree of each parameter](image)
The impact factor on the maximum temperature $T_{\text{max}}$ is greater in the order of the number of fin, the number of LED chips, the material of fin, the height of fin and the thickness of the substrate, that is the order of cooling effect.

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

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 no cylinder, that is the open type which prevents the increase of inner temperature.

The calculated result by FEM showed a maximum temperature $T_{\text{max}}$ of 38℃. The worst model shown in Fig. 6 has smaller area of fin, and has only on LED chip placed at the center of the substrate, made of austenitic steel with lower heat conductivity. The maximum temperature $T_{\text{max}}$ in the case was 186℃. Consequently, the difference between the best and worst models was found to be greater than 120℃.

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 43℃. The model has a little simpler fin structure and has the open 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.

### Table 4 Parameter of each model

| Parameter                                | Best          | Reasonable | Worst         |
|------------------------------------------|---------------|------------|---------------|
| with/without cylinder                    | without      | without    | with          |
| the number of fin                        | 24            | 24         | 3             |
| the height of fin (mm)                   | 20.5          | 15.5       | 10.5          |
| the thickness of fin (mm)                | 1             | 1          | 1             |
| the thickness of substrate (mm)          | 3             | 3          | 1             |
| material                                 | Cu            | Al         | SUS304        |
| inner temperature                        | 22            | 22         | 45            |
| the number of LED chips                  | 6             | 3          | 1             |
| maximum temperature (°C)                 | 38            | 43         | 186           |
| minimum temperature (°C)                 | 37            | 40         | 51            |
4. Conclusion

With regard to a LED bulb with an diameter of 60mm and a power of 6 watt, the effect of the heat dissipation structure, 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 was analysed 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 impact factor on the maximum temperature of the LED chips is greater in the order of the number
2. It was confirmed that the open type structure without outer cylinder is 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. The calculated result with the FEM method was analyzed the regression analysis, and then the regression equation was formed to estimate the maximum temperature. Using the equation, without the change of CAD diagram and the FEM analysis

References
[1] Nozawa T 2008 Nikkei Electronics Nov.3rd pp 87-97
[2] Office of Energy Efficiency and Renewable Energy, U.S. Department of Energy, July 2011, Solid-state Lighting Research and Development: Manufacturing Roadmap
[3] Qin Y Y and Ron Hui S Y 2010 Comparative Study on the Structural Designs of LED Devices and Systems Based on the General Photo-Electro-Thermal Theory IEEE Trans. Power Electronics 25 pp507-513
[4] Chou H and Yang T 2007 Development of Junction Temperature and Driving Current upon Emission Spectra of LEDs Proc. 1st Int. Conf. White LEDs and Solid State Lighting pp202-
[5] Osawa S, Izumi M and Sakamoto S 2010 Toshiba Technical Review 65 7 pp 8-11
[6] Kobayashi T, Sakate Y, Hashimoto R, Takashina T, Kanematsu H, Mizuta K and Utsumi Y 2012 Research on optimization of cooling structure of LED element The-Asia-Pacific Interdisciplinary Research Conference Irago,Japan
[7] Cybernet systems co., ltd., 2010, ANSYS, Retrieved from http://www.cybernet.co.jp/ansys/