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INVESTIGATION OF TEMPERATURE REGIME AND LUMINOUS FLUX OF LIGHT-EMITTING ELEMENT OF LIGHT EMITTING DIODE LAMP

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ABSTRACT

The article presents the results of computer simulation of heating regime, experimental investigation of temperature pattern and luminous flux of the stripe-patterned light-emitting element of LED lamp with convection gas cooling. Computer simulation of heating regime was carried out with the help of CFD software using the finite element method (FEM); luminous intensity distribution curve was simulated by means of optics simulation program. The experiments were performed using a thermal imaging camera and goniophotometer. The light emitting element is a thin sapphire substrate having a chip-on-board (COB) LED array disposed thereon. Studies have shown that temperature increases linearly with the forward current increase, reaching 155°C at the rated operating conditions. Luminous flux ceases to increase significantly at a current of 22.5 mA. The article has discussed the results and proposed possible options for optimizing the heating regime of the light emitting element.

Keywords: light emitting element, heating regime, luminous flux, chip-on-board, light-emitting diode.

INTRODUCTION

LED lighting is currently taking its position in the modern world much more steadily in various spheres of human life. LEDs are applied in automobile headlights, billboards, computer and smart phone displays, street lamps, lighting in homes, offices and industrial facilities. The numerous advantages of light emitting diode light source are duly appreciated, and light-emitting diodes (LEDs) are gaining more and more popularity owing to the higher efficiency, the absence of pulsations, durability, etc. However, despite the obvious advantages of LEDs, there are a number of reasons limiting the widespread use and their complete replacement of other light sources, such as: incandescent, fluorescent and halogen lamps. One of the reasons is the high cost of LED lamps as compared to the conventional incandescent lamps. This is partly due to more complex manufacturing technologies. In this paper we consider promising design of LED lamps, which, in essence, is a hybrid of incandescent lamp and LED lamp. This approach will enable to use the proven technology of mass production of incandescent lamps to the maximum extent possible and all the advantages of an LED light source. On the one hand, the design of the conventional incandescent lamp aims at attracting consumers to the new LED lamps, on the other hand, it will provide a low cost and a slight upgrading of equipment of incandescent lamp manufacturers.

It is expected to receive a full-featured LED lamp in the conventional version at an affordable price, as a result. The second and no less important problem of almost any LED device is to provide a normal heating regime. Holger Pross (Pross, 2010) describes the basic LED failure causes. Majority of these failures is associated with unacceptable operating temperatures. As a result of failure to comply with the required operating conditions many of LED advantages disappear. Luminous flux decreases dramatically; the service life is reduced many-fold, as a rule, the LED starts flashing. Insufficient attention to the problem of heat removal often leads to such unpleasant consequences, and has an adverse effect on the reputation of this promising light source.

The light emitting element is a chip-on-board (COB) LED array mounted on a thin sapphire substrate covered with one common phosphor layer (He, 2014). Such approach allows placing light-emitting elements inside the glass bulb. However, usage of COB technology entails some difficulties, in particular non-uniform distribution of the substrate temperature pattern. To determine the thermal parameters of the element, it is expedient to use computer simulation, which is based on the application of the finite element method (FEM) (Wen, 2014), and then confirm the experimental research of the light emitting element characteristics. For example, the article devoted to the analysis of LEDs thermal power fluorescent (Lee, 2014) justifies the use of computer simulation to determine and optimize the heating regime of the COB LED arrays. Thus, the present paper at first implements the mathematical model of light-emitting elements, and then performs an experimental analysis of the temperature pattern distribution and studies changes in the luminous flux.

PROBLEM FORMULATION

To determine the temperature regime of the stripe-patterned light emitting element it is necessary to measure the dependence of heating from forward current, the dependence of the luminous flux from the forward current, as well as to determine the temperature pattern distribution. Experimental determination of the temperature dependence against the forward current magnitude was conducted using a thermal imaging camera. To approximate the conditions under which the experiment was conducted, an experimental model was fabricated in the form of a case made of organic glass (plexiglass), simulating a closed internal volume of LED lamp glass bulb. The layout has a hole for attachment of the thermal imaging camera lens. An ammeter and a voltmeter were connected for continuous monitoring. Measurements of the LED element temperature with the thermal imaging camera enable to determine the maximum temperature of the element, as well as an image for the visual representation of the temperature pattern distribution on the surface of the investigated object. However, measurements with a thermal imaging hardware do not provide data on the temperature pattern distribution inside the light emitting element. Another disadvantage of the experiment with the thermal imaging camera is low resolution of the device. By virtue of the fact that the light emitting element has small dimensions 40x2x0.45 mm, an image obtained using the thermal imaging device is uninformative. In this connection it is proposed to use computer simulation to investigate the temperature pattern distribution.

Simulation was carried out in Autodesk Inventor 2015, computer-aided design (CAD) system and Autodesk Simulation CFD 2015, computer-aided engineering system (CAE), (licensed for educational institutions). Light characteristics were measured using a goniophotometer. Similarly to the experiment with a thermal imaging hardware luminous flux measurements were carried out. The data obtained during the experiment allow determining variation of the luminous flux magnitude with the forward current intensity, which in turn will enable to determine the favorable operation mode for the stripe-patterned light emitting element of LED lamp with convection gas cooling.

THEORY

Model investigation was carried out in order to simulate temperature pattern of light emitting elements. Major part of heating energy generated by LED chips is transferred to the environment by means of heat removal from the substrate. This assumption allows the use of a heat model of the plate $l \times k \times p$ in size with three-dimensional temperature pattern $T(x, y, z)$, heat exchange on the lateral surfaces and n local sources occupying the area of ($x_{i1}<x_i<x_{i2}$, $y_{i1}<y_i<y_{i2}$, $0<h_i<h$). Steady-state thermal conductivity equation is defined as follows:

$$\frac{\partial}{\partial x}\left(k_x \frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(k_y \frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(k_z \frac{\partial T}{\partial z}\right)+\sum_{i=1}^{n} q_i = 0, \quad (1)$$

where$T$ and $q_i$characterize the temperature and heat flux from the chips, k_x, k_y and k_z– material thermal conductivity in the directions of coordinate plane X, Y and Z, respectively.

Let us write heat flux density distribution of the i-th chip as:

$$q_i = \begin{cases} \dfrac{P_i}{(x_{i2}-x_{i1})\cdot(y_{i2}-y_{i1})\cdot h}, \\ 0, \quad \text{outside the chip area}, \end{cases} \quad (2)$$

where P_i - heat output of the i-th chip; x_{i1}, x_{i1}, y_{i1}, y_{i2} - geometrical coordinates of chip reference points on the substrate; h - chip height.

Third type boundary conditions are specified on the substrate surfaces:

$$\mp k_x \frac{\partial T}{\partial x} = \alpha(T_{\text{CP}} - T),$$

$$\mp k_y \frac{\partial T}{\partial y} = \alpha(T_{\text{CP}} - T), \quad (3)$$

$$\mp k_z \frac{\partial T}{\partial z} = \alpha(T_{\text{CP}} - T),$$

where α -integrated heat-transfer coefficient; T_{CP} - ambient temperature; T - surface temperature.
The initial condition is given by:

$$T\big|_{\tau=0} = T_0(x, y, z). \quad (4)$$

The required function in the problem (1) – (4) is $T(x, y, z, \tau)$, specified in the continuous area:
$\Omega = \{0 \le x \le l\}\times\{0 \le y \le k\}\times\{0 \le z \le p\}\times\{0 \le \tau \le \tau_{\max}\}$.

Computer analysis takes into account two heat transfer mechanisms: natural convection and thermal conductivity. Ambient temperature at the initial moment was 25°C.

EXPERIMENTAL RESULTS

Experiments were conducted with several samples of the light emitting elements, and the measured parameters of the light-emitting elements varied within a wide range. In this connection the samples with the most repetitive parameters were selected. The results of a series of experiments were tabulated and the mean values were derived.

As a result of the experimental determination of thermal characteristics dependence on the forward current magnitude the data were obtained which are given in Table-1. The thermal imaging hardware (Figure-1) was used to implement the visual part of the experiment at the voltage of 74.8 V and the forward current of 20 mA. The specified voltage and current valuesare the stated rated operating conditions of the 1.5 W light emitting elements.

Table-1. Temperature versus forward current magnitude.

U, V	I_F, mA	T, °C
66.3	2.5	42
66.9	5	56
67.2	7.5	71
68.4	10	86
69.5	12.5	101
70.7	15	118
72.1	17.5	135
74.8	20	155
76.3	22.5	174
78.2	25	197

Figure-1. Temperature pattern distribution.

Luminous flux measurements were conducted similarly using a goniophotometer. The obtained results were used as initial data for computer simulation of the luminous flux. Simulation algorithm can be described briefly by the following actions: building a geometric model of the light emitting element, specifying characteristics according to the data obtained in the course of the experiment and then analyzing the results. Experimental results are given in Table-2.

Table-2. Luminous flux versus forward current magnitude.

U, V	I_F, mA	Φ, cd
66.3	2.5	2.3
66.9	5	3.99
67.2	7.5	6.42
68.4	10	8.56
69.5	12.5	10.52
70.7	15	11.24
72.1	17.5	13.74
74.8	20	13.52
76.3	22.5	14.85
78.2	25	15.23

For better perception of the experimental results the data are presented in the form of two graphs on the same coordinate plane (Figure-2). The solid line shows a graph of the luminous flux versus current and respectively a dotted line demonstrates the temperature-current dependence.

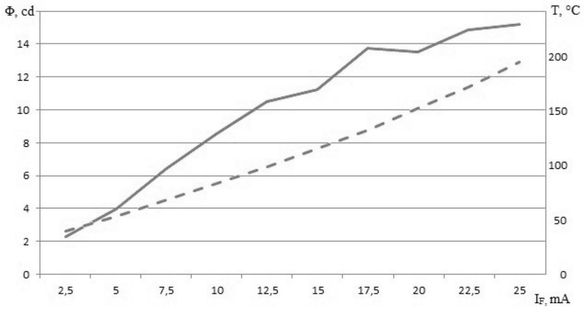

Figure-2. Graphs of luminous flux and temperature versus current.

Computer simulation results provide the information about temperature pattern distribution throughout the entire light-emitting element (see Figure-3).

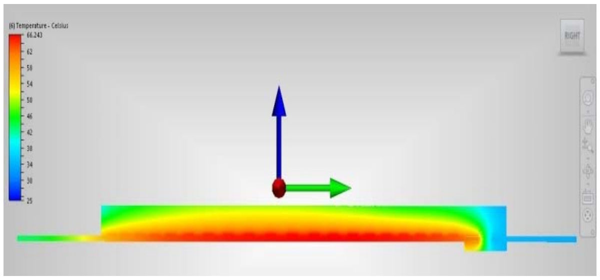

Figure-3. Computer simulation results.

Figure-3 demonstrates temperature pattern distribution obtained by means of CFD software. The maximum design temperature is 66.2°C. This temperature corresponds to the decreased value of the chip-generated heat energy - this is due to the fact that at the decreased value of generated heat energy the temperature gradient is visualized more clearly and the locations of increased and decreased concentrations of heat energy can be estimated throughout the volume of the light emitting element of the LED lamp with convection gas cooling.

DISCUSSIONS

The experimental results have quite large data scattering, this may indicate that the manufacturing technology of such light-emitting elements has been developed insufficiently yet. In part, this is a plus for researchers working on the subject, because the design is imperfect and gives full scope for improvement.

Figure-2 bears the most informative component of the pilot study. It can be seen that at a nominal current of 20 mA the temperature is 155°C. According to (Pross, 2010), this temperature is critical, indicating the obviously increased nominal value of the forward current. One should also note the uneven distribution of temperature pattern, which adversely affects the functioning of the stripe-patterned light emitting element. Firstly, different operating temperatures of LED chips have a direct impact on the stability of the light output $\Delta\eta$. It has been experimentally proved that at typical temperatures of the *p-n*-junction of the chip in the finished structure (+70…+100 °C) light output makes 85–90% of the value at a temperature of +25°C. Secondly, at various operating temperatures of the chip preliminary binning of light emitting diodes does not give a noticeable effect as it is performed at the same temperature of the *p-n*-junction equal to +25 °C (Paul, 2010). Therefore, it becomes urgent to provide high temperature stability of LED thread parameters - light output, $\Delta\eta$, and color temperature, ΔT_C.

CONCLUSIONS

Based on the conducted research the following conclusions can be made: to ensure the normal operation of the stripe-patterned light emitting element of the LED lamp with convection gas cooling it is necessary to reduce the magnitude of the forward current down to 13 mA. In this case luminous flux is reduced slightly, and temperature regime ensures reliable operation of the LED device. It is also necessary to rectify the situation with the uneven distribution of the temperature pattern of the light emitting element.

Optional solutions to the above problems include the following methods: usage of the material with higher thermal conductivity as a substrate for more effective heat removal from the LED chips into the environment, usage of the gas having high thermal conductivity as gaseous atmosphere to increase the efficiency of the convection heat transfer from the light emitting element to the walls of the glass bulb, change of the substrate geometry and others.

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