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RESEARCH AND MODELLING ON ELECTRICAL AND THERMAL MODE OF LEDS OPERATION IN THE LUMINAIRE

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ABSTRACT

In the article, the electrical and thermal processes in the LED lamp with varied parameters are investigated. Voltage and current measurements on all LEDs of the luminaire are carried out in the nominal operating mode. The power allocated to each LED is determined. The calculation of the LED crystal temperature was carried out using the developed thermal LED model based on the results of the measurements and by using "Multisim" program. It has been established that the temperature of the crystals of individual LEDs in the luminaire differ significantly, which leads to unfavourable thermal conditions for them and an increased likelihood of premature failure.

Keywords: LED, LED luminaire, voltage, current, power, current-voltage characteristic, crystal temperature

1. INTRODUCTION

Ensuring high reliability and the service life of LEDs lamps and luminaires declared by the manufacturer is one of the main tasks of modern electronics and lighting technology. The service life of an individual LED operating in nominal mode can reach 100 thousand hours. Many manufacturers of LED light sources indicate a similar lifetime for their products without conducting the relevant studies. The main deception for the consumer is this, because at the moment the real life of LED lamps and lamps does not exceed 50 thousand hours. On the one hand, this is due to the reliability of the driver, in which many manufacturers of LED products are trying to save by using substandard devices. On the other hand, there are problems associated with ensuring the reliability of the LEDs themselves, even if the ideal driver is used for their power supply.

The values of electrical and thermal parameters of LEDs can vary within 10 % due to the instability of the technological process of production. In order to determine the effect of variation in the values of the parameters on the operation modes and the service life of the LED light source, a study was made of the processes taking place in the real lamp. The luminaire of the Russian-Korean company NEPES RUS is selected as the test sample. The rated power is 50 watts. The luminaire includes 40 LEDs, which are included in a series-parallel group. Lifetime of the lamp, according to the manufacturer, is 70 thousand hours [1, 2]. Operating temperature range is from –20 ºC to +50 ºC. Blue LEDs, produced by the company Semi LEDs, are used in the luminaire. The LEDs are rated for a rated direct current of 350 mA and a power rating of 1 W [3]. The scheme of switching on the LEDs in the luminaire is shown in Fig. 1.

The electrical circuit of connecting the LEDs in the luminaire is a parallel connection of four branches, each of which contains ten LEDs in series. The photograph of the design of the LEDs light module is shown in Fig. 2.

All the LEDs are located on the same printed circuit board, made of fibre glass. LEDs are mounted

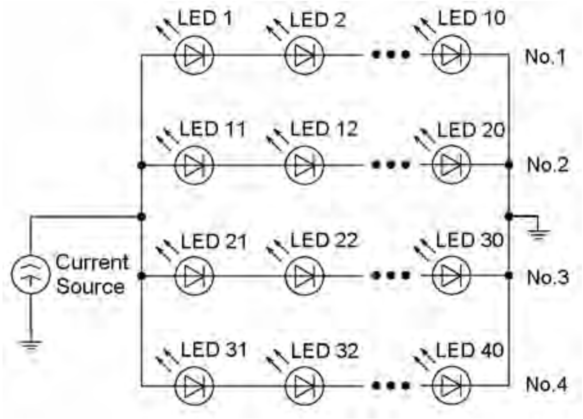

Fig. 1. Diagram of LEDs in the luminaire

on the surface of the printed circuit board using surface mounted technology. The circuit board is attached to the metal housing of the luminaire. Additional measures for cooling LEDs are not provided [3].

2. METHOD

Measuring the thermal processes in the luminaire and LEDs is quite difficult. The solution is to calculate the thermal processes based on the measurement of electrical processes and data on the design of the luminaire and LEDs. The thermal processes occurring in the LED are calculated according to the theory of heat transfer. The methods for determining the temperature fields in the construction of the LED are based on this theory. Thermal processes are described by a system of differential equations of heat conduction. The number of elements in the construction of the LED housing determines the order of the system [3]. Three main methods exist for solving the system of differential heat equation:

1) Analytical method;
2) Approximate numerical methods;
3) The method of electro thermal analogy.

The first method is used when it comes to bodies with simple geometry and structure, with unchanged values of thermo physical parameters, a simple analytical expression of boundary conditions and a source of thermal energy. However, when using the presented method for real light emitting diodes, it is necessary to simplify considerably the mathematical description of thermal processes. This affects the final result, which makes it possible only to assess the nature of the course of the heat transfer process.

Numerical or analogy solution methods are used to improve the accuracy of calculations. These methods are mathematical and physical modelling. The result of numerical methods is only an approximate solution. The temperature field is calculated for the specific points of the element and is represented as a tabular value.

The method of electro thermal analogy (ETA) is based on the analogy of differential equations of the electric and temperature fields. The ETA method provides that the heat capacity of the structural element is replaced by the electrical capacity proportional to it, and the thermal resistance by the electrical resistance. The electric current is taken as the analogue of the power released when an electric current flows through the LED chip in the ETA method. The potentials of the circuit nodes correspond to the superheat temperature of the corresponding structural element. Each element of the device design in the model is replaced by a T-shaped RC-chain. The combination of these RC-circuits forms a thermal model of the LED design. All the electrical processes taking place in this scheme reflect the thermal processes in the LED [4].

The following assumptions were adopted in the development of the thermal model:

1. The temperature field in the structure and the electric field in the model are one-dimensional;

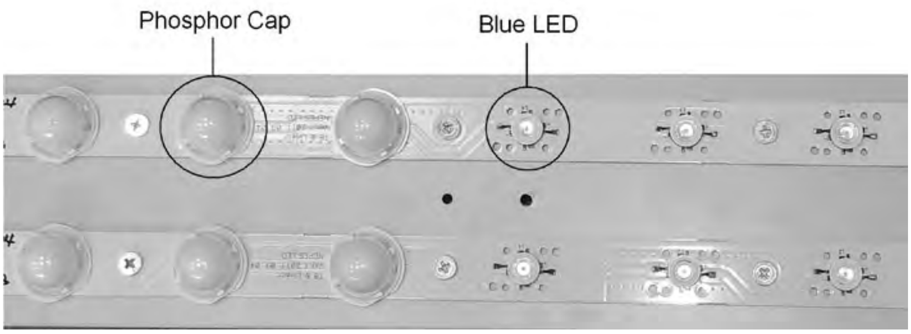

Fig. 2. The design of the LEDs light module

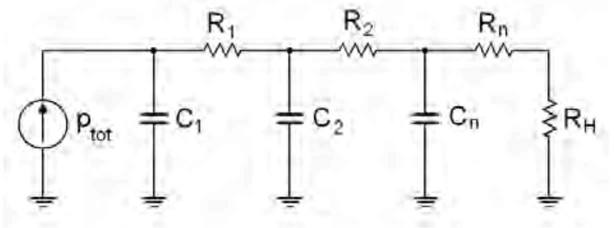

Fig. 3. Generalized analogue of the LED design

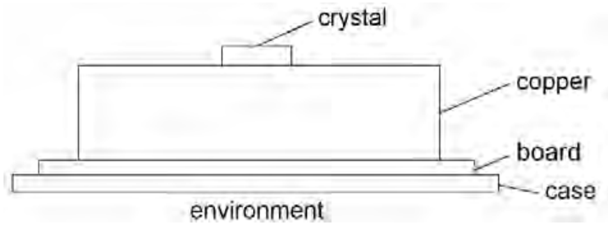

Fig. 4. Simplified LED design

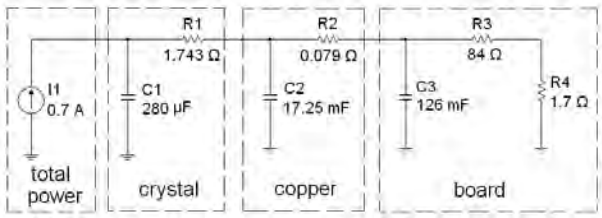

Fig. 5. Thermal model of the LED in “Multisim”

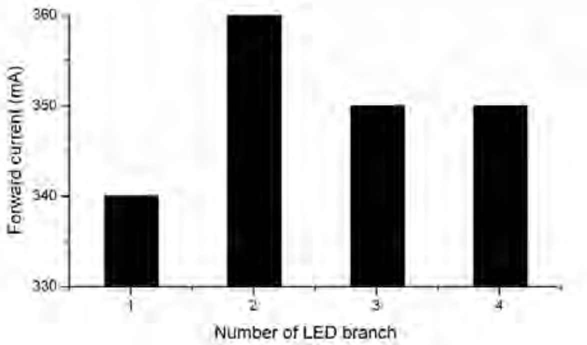

Fig. 6. Current distribution along the parallel branches of the luminaire

2. The material of the crystal and other elements of the LED design is homogeneous and isotropic with respect to thermo physical properties, and these properties do not depend on temperature;

3. All thermal energy is dissipated in a layer of an infinitesimally thin crystal passing through its centre parallel to the ends;

4. The temperature of all elements of the structure is steady and identical at the initial moment.

The equivalent T-shaped RC-chain corresponds to a certain element of the LED design in the model. The circuit consists of two series resistors RI and a capacitor CI. Capacitance capacitor CI corresponds to the heat capacity of the I-TH element of the structure. Resistance RI corresponds to the thermal resistance of this element. The values of resistance RI and capacity CI for an element of area S and length l were calculated as follows [5, 6]:

$$R_i = \frac{l_i}{k_i \cdot S_i}, \tag{1}$$

$$c_i = \rho_i \cdot c_0 \cdot S_i \cdot l_i, \tag{2}$$

where ρ is the density; c_0 is the specific heat; k is the coefficient of thermal conductivity.

The resulting model of the LED is an electrical circuit (Fig. 1) consisting of series-connected T-shaped RC-circuits.

The following notation is introduced in Fig. 3: P_{tot} is the loss capacity; Rn is the equivalents of the element’s thermal resistance; C_n is the equivalent heat capacity of the element; R_H is the edge cooling conditions on the radiator side.

The creation of a complete electro thermal LED model is possible in a certain environment of mathematical modelling of electrical processes using the ETA method. Thermal parameters are represented by their electrical analogies, which allows for a reverse thermal connection between the electric and thermal models taking into account the scale factors for the recalculation of these quantities. A similar feature of the application of the ETA method makes it possible to investigate the electro thermal processes taking place in both individual LEDs and in LED lamps and luminaires in general. This can not be obtained by using standard element libraries that exist in simulation programs for electrical processes.

The proposed approach is the basis for the thermal model of the LED, which is part of the electro thermal model created in the “Multisim” program. Let us consider in more detail the process of developing this thermal model.

The simplified design of this LED is shown in Fig. 4, given that it is attached to a printed circuit board that acts as a cooler.

The LED design is a crystal based on gallium nitride (*GaN*), which is located on a copper substrate. The printed circuit board, on which the LEDs are located, quite often acts as a cooler for modern LED

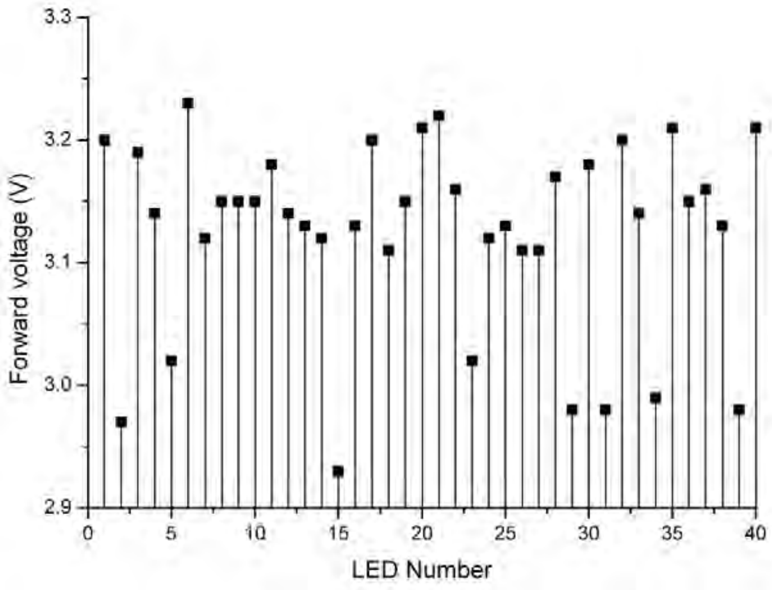

Fig. 7. Distribution of values of direct voltage on the LEDs of the luminaire

light fixtures. The calculation is carried out for this case.

The substitution scheme for the thermal model, performed using the ETA method in the "Multisim" software environment, is shown in Fig. 5 [7, 8].

Fig. 5 shows that the DC source is at the input of the circuit and is analogous to the electrical power loss, which is released on the LED. The value of this power is 0.7 W, taking into account the efficiency of the LED, equal to 30 %. Further, RC circuits, which are analogies of a crystal, a metal substrate and a printed circuit board, follow in the model. The values of resistors and capacitors in the developed model were calculated as follows [9].

The crystal dimensions are for the selected LED: height 0.145 mm, length 0.8 mm, width 0.8 mm. The specific heat conductivity of *GaN* is 130 W / m • K, the specific heat is 0.49 J / g • ºC, the density is 6.15 g / cm3. Substituting these values into formulas (1) and (2), the following values of the thermal resistance of the crystal-metal substrate and the heat capacity of the crystal are: R1 = 1.743 ºC / W and C1 = 280 μJ / ºC.

The dimensions of the copper substrate are equal: height 0.4 mm, diameter 4 mm. The specific thermal conductivity of copper is 401 W / m • K, the specific heat is 385 J / g • ºC, the density is 8.92 g / cm^3. Substituting these values into formulas (1) and (2), the following values of the thermal resistance of the metal substrate-printed circuit board and the heat capacity of the copper substrate yield: R2 = 0.079 ºC / W and C2 = 17.25 mJ / ºC.

The dimensions of the section of the printed circuit board made of fiberglass, which is involved in the heat exchange process are: height 1.2 mm, diameter 7 mm. The specific thermal conductivity of the fibreglass is 0.37 W / m • K, the specific heat is 1470 J / g • ºC, the density is 0.185 g / cm^3. Substituting these values into formulas (1) and (2), the following values of the thermal resistance of the printed circuit board-environment and the heat capacity of the printed circuit board yield: R3 = 85.7 °C / W and C3 = 126 mJ / °C.

Thus, the calculation of the main components of the thermal model is carried out. The temperature value of each structural element can be measured with the XSC1 oscilloscope, since the voltage is the equivalent of temperature.

3. RESULTS

Investigation of the luminaire (Fig. 2) was carried out in the nominal mode of its operation, when a current of 1.4 A flows through it. This current should be evenly distributed across each parallel branch of the LEDs when there is no variation in the values of the LED parameters. Thus, the current flowing through each LED should be equal to the nominal value of 350 mA. However, the current values are distributed differently in real light fixtures. The measurement is based on the values of the current flowing in each parallel branch of the LEDs in the luminaire. The driver current distribution along the parallel branches is shown in Fig. 6.

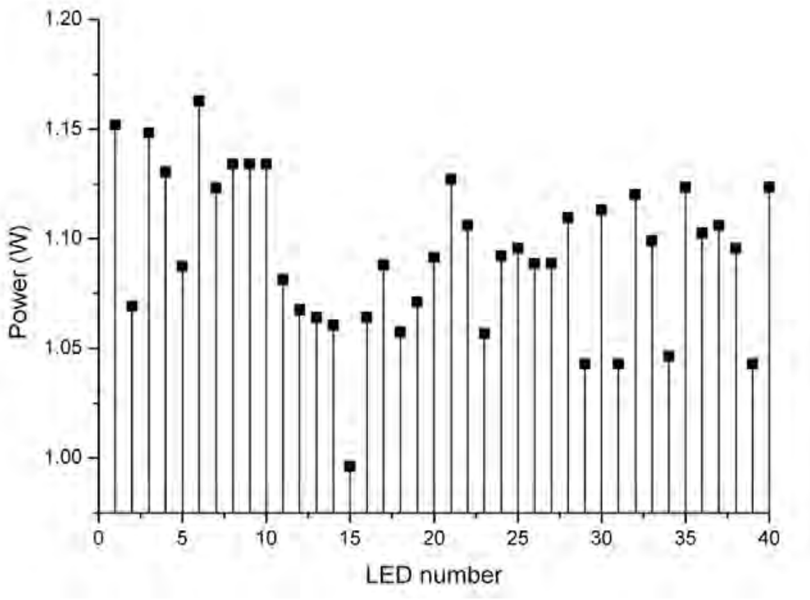

Fig. 8. Variation of the power, which is released in the LEDs crystals

Fig. 6 shows that the currents flowing through parallel branches No. 2 and 3 differ from the nominal value of 350 mA and are equal, respectively, to 360 mA and 340 mA. Thus, the LEDs of these branches operate in modes other than the nominal mode, due to the presence of a technological spread of the values of their parameters.

Consider the processes that occur in the LEDs of each parallel branch. Since the current flowing through the LEDs of the branch is the same, it is of interest to consider the variation of the values of the direct voltage drop across them. Measurement of voltage values is carried out on each LED of the luminaire at the values of the current flowing through them, shown in Fig. 6. The results of the measurement are shown in Fig 7.

Fig. 7 shows that a significant variation in the values of direct voltage on the LEDs is observed in the luminaire. The maximum value of the forward voltage is observed on the LED № 6 ($U_{F№\,6}$ = 3.23 V). The minimum value of voltage was obtained on the LED № 15 ($U_{F№\,15}$ = 2.93 V). The values of the forward voltage vary considerably within a single branch of the LEDs, despite the fact that the same current flows through them. The maximum variation in the values of the forward voltage is observed in branch No. 2 and it is equal to 0.25 V.

Variations in the magnitude of the current flowing through the parallel branches of the LEDs and the direct voltage on them lead to the release of different power values in their crystals. Variations in the power values, which are released in the crystals of the LEDs of the light, are shown in Fig. 8.

It can be concluded from Fig. 8 that a significant variation in the power values emitted in LED crystals is observed in the lamp under study. The power value did not exceed the nominal value of 1 W and was 0.99 W on the LED No. 15. Power significantly exceeding the nominal value of 1 W is allocated on the LEDs of parallel branches No. 1 and 4, through which the rated current of 350 mA flows. The maximum power value is allocated in the crystal of LED No. 6 and is 1.16 W, which is 16 % higher than the nominal value.

Thus, the variation and excess of the nominal value of the power released in the crystals of the luminaire's LEDs leads to the appearance of unfavourable thermal regimes of their operation.

The electro thermal model of the LED used in the test fixture was developed to investigate the thermal operating conditions in the Multisim software environment. The design of the luminaire was also taken into account when creating a thermal model. The results of simulation of the transient process of changing the temperature of LEDs No. 5, 6 and 15 are shown in Fig. 9. The maximum (1.16 W), average (1.08 W) and minimum (0.99 W) power is allocated in the crystals of these LEDs (Fig. 8). The initial value of the crystal temperature of the LEDs is 20 °C. The efficiency of the LEDs, equal to 30 %, was taken into account in the simulation. This efficiency shows that 70 % of all energy supplied to the LED is allocated as heat in the crystal.

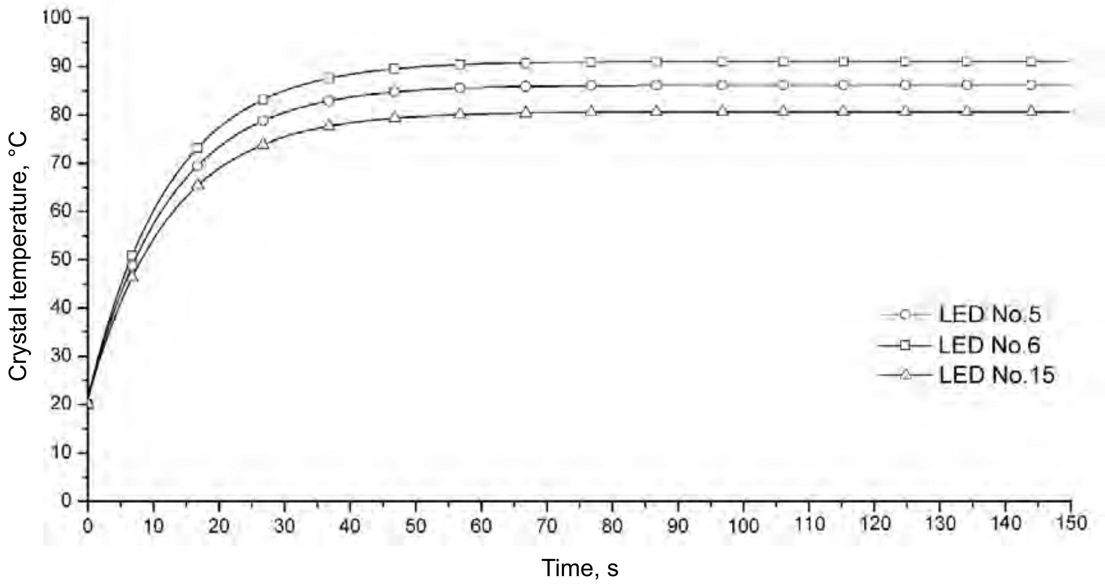

Fig. 9. Time dependences of crystal LED temperature

Fig. 9 shows that the transient process ends at the instant of time equal to 150 s, and the temperature of the LED crystals reaches the following values: $T_{j№\,6}$ = 92 ºC; $T_{j№\,5}$ = 87 ºC; $T_{j№\,15}$ = 82 ºC. The maximum scatter in the crystal temperature of the luminaire's LEDs was ΔT_{jmax} = 10 ºC.

4. DISCUSSION

Such a variation of crystal temperature values, at first glance, does not pose a danger to LEDs, since the maximum permissible temperature of the crystal is +125 ºC in accordance with the passport data. However, LEDs degrade over time, and their parameters and characteristics deteriorate significantly during operation. In [10, 11], a study was made of the dependence of the lifetime of various LEDs on the crystal temperature. It is established that the service life of the blue LED is 25 thousand hours longer at a crystal temperature of 80 °C than at a temperature of 90 °C. In addition, the variation in the values of the parameters of the LEDs will increase due to the spread of the crystal temperature values, which will lead to an even greater discrepancy in the temperature values. Thus, the likelihood that the lamp will work claimed by the manufacturer 70 thousand hours, is extremely small.

There are no specific methods and ways to solve this issue for manufacturers of LED products at the moment. Only attempts are made to correct the effect of the problem, while nothing is done to prevent the cause. It is easier for manufacturers to provide the customer with favourable warranty conditions and in case of failures replace defective lamps with new ones. However, not every consumer has the ability and desire to periodically disassemble the lighting system to replace the fixtures. This problem causes a significant impact on the reputation of LED products in general.

4. CONCLUSIONS

Preliminary studies have shown that for the same electrical and thermal operating modes of the LEDs as close as possible to the nominal, it is necessary, first of all, start exercising binning on a complex light, electrical and thermal properties at the stage of their production. LED lamps are formed from LEDs belonging to one bin at the present time. However, light emitting diodes are blown mainly by light parameters, such as luminous flux, brightness and correlated colour temperature. The main electrical parameter, by which the bin is made, is a direct voltage drop. Despite this, the conducted research revealed the presence of a variation of this parameter in the LEDs of the luminaire. Binning is not conducted at all on the values of thermal parameters. As a result, LEDs with identical values of the parameters of light, but with significantly different values of the electrical and thermal properties, can be branches in the same lamp. Accordingly, different energy will be released as heat in the crystals of such LEDs. The heat from the crystal will also be at different intensities, due to the variation in the values of the thermal parameters, the most important of which is the thermal resistance of the crystal-shell in the steady state. This leads to differences in the thermal conditions of the individual LEDs of the luminaire and a reduction in its service life.

A study conducted on the example of a Russian-Korean LED lamp showed that the problem of variation in the values of the parameters of LEDs in luminaires does exist. This leads to a discrepancy between the thermal operating modes of the LEDs. These processes will lead to a reduction in lamp life. The amount by which the service life will be shortened depends on the degree of divergence of the thermal regimes of the individual LEDs. Thus, the LED luminaire can work out declared by the manufacturer 70 or 100 thousand hours only in the event that all its LEDs work in the same nominal modes. This can not be achieved at the moment in practice, taking into account the applied methods of the bin.

REFERENCES

1. Hamon B., van Driel W.D. LED degradation: From component to system/ Microelectronics Reliability, 2016, 64, pp. 599–604.

2. Qu X., Wang, H., Zhan X., Blaabjerg F., Chung H.S.-H. A Lifetime prediction method for leds considering real mission profiles/ IEEE Transactions on Power Electronics, 2017, 32, pp. 8718–8727.

3. Bespalov N.N., Kapitonov S.S., Kapitonova A.V. Research of processes in the LEDs luminaire in case of the voltage temperature coefficient of separate LEDs variation/ Light & Engineering, 2016, V.24, #4, pp. 72–75.

4. Bespalov Nikolai N., Ilyin Mikhail V., Kapitonov Sergei S. Testing equipment for LED luminaire control devices and fluorescent lamp electron ballasts/ Light & Engineering, 2017, V. 25, no. 4, pp. 86–91.

5. Kapitonov Sergei S., Kapitonova Anastasia V., Grigorovich Sergei Y. Temperature dependence modeling for powerful LED characteristics in Multisim/ ARPN Journal of Engineering and Applied Sciences, 2017, V. 12, no. 10, pp. 3328–3334.

6. Bai K., Wu L.G., Nie Q.H., Dai S.X., Zhou B.Y., Ma X.J., Zheng Z.Y., Zhang F.W. Thermal simulation and optimization of high-power white LED lamps / International Conference on Electronics, Communications, and Control, ICECC Proceedings, 2011, pp. 573–576.

7. Kapitonov S. S., Kapitonova A.V., Grigorovich S.Y. Development of thermal LED model / Journal of Fundamental and Applied Sciences, 2017, V. 9(7S), pp. 752–762.

8. Alexeev V.P., Belousov A.V. Features of electric and mechanical systems electrothermal models in the method of electrothermal analogy. Proceedings of the 8th International Scientific and Practical Conference of Students, Post-Graduates and Young Scientists: Modern Technique and Technologies 2002, pp. 93–95.

9. Ishizaki S., Kimura H., Sugimoto M. Lifetime estimation of high power white LEDs / Journal of Light and Visual Environment, 2007, 31, pp. 11–18.

10. Yang L., Hu J.b, Shin M.W. Degradation of high power LEDs at dynamic working conditions / Solid-State Electronics 2009, 53, pp. 567–570.

11. Koh S., Yuan C., Sun B., Li B., Fan X., Zhang G.Q. Product level accelerated lifetime test for indoor LED luminaires / 2013, 14th International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems 2013, pp. 652–999.

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