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DEVELOPMENT OF THERMAL LED MODEL

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ABSTRACT

One of the main tasks of modern lighting technology is to increase the reliability of LED technology. In order to solve this problem, it is necessary to ensure an effective cooling of LEDs, since the values of their parameters depend substantially on the temperature of a crystal. This dependence makes a significant effect on the reliability of a lamp or a luminaire. Thus, in order to increase the reliability of LED technology, it is necessary to calculate the thermal operating conditions of LEDs at the design stage, taking into account a cooling system in use. There are many programs designed to simulate thermal processes, however, such programs use primitive, substantially simplified LED models, and do not allow to recreate electrical and thermal regimes close to real ones. In order to conduct a more accurate simulation, it is required to create new electric and thermal models of LEDs, which are based on real values of the electric-physical and geometric parameters of the instruments. The article considers the thermal model of LED produced by the company SemiLEDs developed in the Multisim program. They performed the calculation of the processes taking place in the light-emitting diodes during their work in a luminaire. The obtained results indicate the possibility of the used approach application for the analysis of various LED light sources. The created models will allow to reveal unfavorable thermal operating modes for LEDs and, accordingly, to take measures to increase the reliability of fixtures.

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1. INTRODUCTION

In recent years, LED light sources have been significantly developed around the world. The field of light-emitting diode application is constantly expanding, there are new markets and consumers of this product. However, LED technology still has certain drawbacks, which limit its use and reduce the quality of lamps and luminaires. One of the main problems of LEDs is the low efficiency. Efficiency does not exceed 30% For most of the currently produced LEDs. Thus, most of the energy supplied to the LED is released in its crystal in the form of heat, which leads to its substantial heating. In order to make a LED work in the nominal mode, it is necessary to ensure a favorable thermal regime of its operation, so the task of an effective cooling provision of the LEDs is one of the main ones in modern lighting engineering. The manufacturers of LED lamps and luminaires solve this problem by increasing the area of a cooler, introducing a substantial reserve in some cases. This leads to the increase in the weight and dimensions of LED technology, which is simply unacceptable for some consumers. In order to optimize the process of a cooler calculation and to ensure the nominal thermal operating mode of the LED light, it is required to have complete information about the thermal processes taking place in it. In order to solve this problem, it is necessary to use modern computer technologies, which allow to study practically any phenomena and processes by modeling, including thermal ones. Nowadays, there is a large number of mathematical modeling programs for electrical and thermal processes. The main problem with all these products is that they tend to be very narrowed concerning their field of use. Some of them are very convenient for thermal process modeling, others - for electrical processes, however, in our case, a universal product is required that allows you to specify both the electrical and the thermal parameters of LEDs and evaluate all the processes taking place in a luminaire promptly. The solution of such a problem is the creation of a universal electric thermal model of an LED light, which will allow to conduct any kind of study. In order to develop this model, Multisim software was selected by "National Instruments" company. This software product has proven itself during the modeling of complex electrical circuits. Besides, an electric model of LED was developed in it. A detailed description of the developed model is presented in [1]. In order to perform a parallel study of the electrical and thermal processes taking place in a

LED light, it is necessary to develop a thermal model of LED. This article describes the process of a thermal model creation in the Multisim program.

2. METHOD

The thermal processes taking place in a LED are calculated according to the theory of heat transfer [2, 3]. Based on this theory, they developed the methods to determine the temperature fields in a LED structure, which are expressed by the system of heat conductivity differential equations. The number of elements in a LED housing determines the order of a system. There are three main ways to solve the system of differential equations for heat conduction [4, 5]:

1) analytical method;
2) approximate numerical methods;
3) the method of electric thermal analogy.

The first method is used when it comes to the bodies with simple geometry and structure, with unchanged values of thermal-physical parameters, a simple analytical expression of boundary conditions and a source of thermal energy. However, when the presented method is used for real light-emitting diodes, it is necessary to simplify the mathematical description of thermal processes significantly, which has an effect on a final result, which makes it possible only to evaluate the nature of the heat transfer process course. In order to improve the accuracy of calculations, they use numerical or analogue methods of solution, which are mathematical and physical modeling.

The result of numerical methods is only an approximate solution. The temperature field is calculated for the specific points of an element and is represented as a table value. The example of such an approach is the grid method. The method of electric thermal analogy (ETA) is based on the analogy of differential equations of electric and temperature field [6]. ETA method provides that the heat capacity of the structural element is replaced by the electric capacity proportional to it, and the thermal resistance is replaced by the electrical resistance. The analog of the power released during the flow of electric current through a LED crystal is the electric current adopted in ETA method. The potentials of the circuit nodes correspond to the superheat temperature of a corresponding structural element. Each element of the device design in a model is replaced by a T-shaped RC-chain. The combination of these RC-circuits forms a thermal model of the LED design, and all the electrical processes taking place in this scheme reflect the thermal processes in a LED.

The following assumptions were accepted during the development of a thermal model [7]:

1) the temperature field in the structure and the electric field in the model are one-dimensional;
2) the material of the crystal and other elements of the LED design are homogeneous and isotropic with respect to thermal physical properties, and these properties do not depend on temperature;
3) all thermal energy is dissipated in the layer of a very thin crystal passing through its center parallel to the ends;
4) at the initial moment the temperature of all elements of the structure is steady and identical.

A certain element of LED design in the model corresponds to the equivalent T-shaped RC circuit, which consists of two sequential resistors R_i and the capacitor C_i. The capacitance of the capacitor Ci corresponds to the heat capacity of the i-th element of the structure. The resistance R_i corresponds to the thermal resistance of this element. The values of resistance R_i and the capacity C_i for the element of the area S and the length l were calculated as follows:

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

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

where ρ is the density; C_0 is the specific heat; k is the coefficient of thermal conductivity.

The obtained model of LED according to ETA method is an electrical circuit (Figure 1) consisting of series-connected T-shaped RC-circuits.

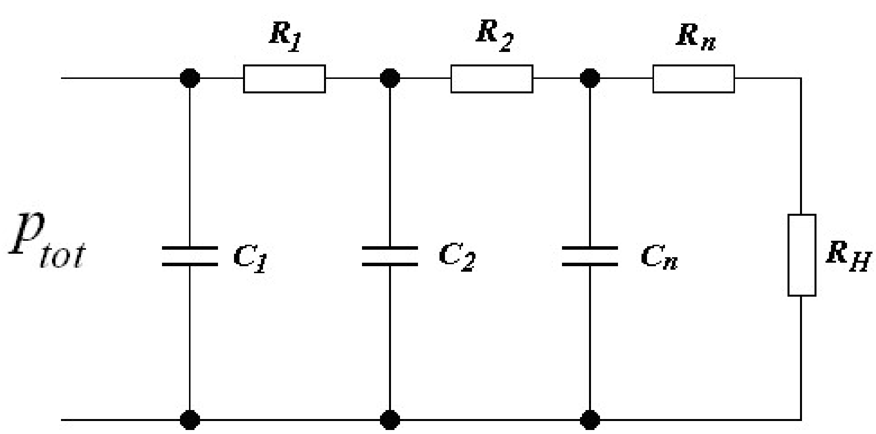

Рис.1. Обобщенный аналог конструкции светодиода.

The following notations are introduced on Figure 1: p_{tot} — loss power; R_n — the equivalents of the element thermal resistance; C_i — the equivalent of the element heat capacity; R_H — edge cooling conditions on the radiator side.

With the application of ETA method it is possible to create a complete electric-thermal LED model in a certain environment of electrical process mathematical modeling, since the thermal parameters are represented by their electrical analogs, which allows to perform a reverse thermal connection between the electric and thermal models, taking into account the scale coefficients of these quantities recalculation. A similar feature of the ETA method application makes it possible to study the electric-thermal processes taking place both in individual LEDs and in LED lamps and luminaires in general, which can not be obtained by using standard element libraries that exist in the programs of electrical process modeling [8].

The proposed approach is the basis for the work of LED thermal model, which makes the part of the LED electrothermal model created in the mathematical simulation environment of the electrical processes Multisim. Let us consider the process of this thermal model development in more detail.

ETA method is universal and suitable for thermal model creation of any LEDs. As the calculation example, we will select a SemiLEDs LED, calculated for the nominal value of a direct current of 350 mA and the power of 1 W [9]. The simplified design of this LED, taking into account that it is fixed to a printed circuit board that acts as a cooler, is shown on Figure 2.

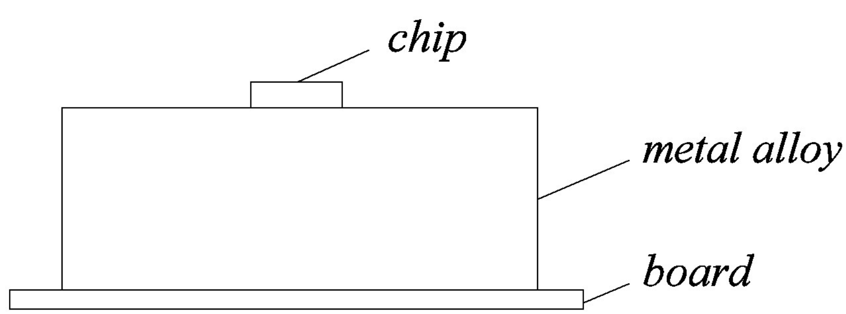

Fig.2. Simplified LED structure

The design of the selected LED is a crystal based on gallium nitride (GaN), which is located on a copper substrate [10]. Quite often a printed circuit board, on which the LEDs are located, act as a cooler in modern LED lights. The calculation was carried out for this case [11].

Figure 3 shows the substitution scheme for the thermal model, performed according to ETA method in the Multisim software environment.

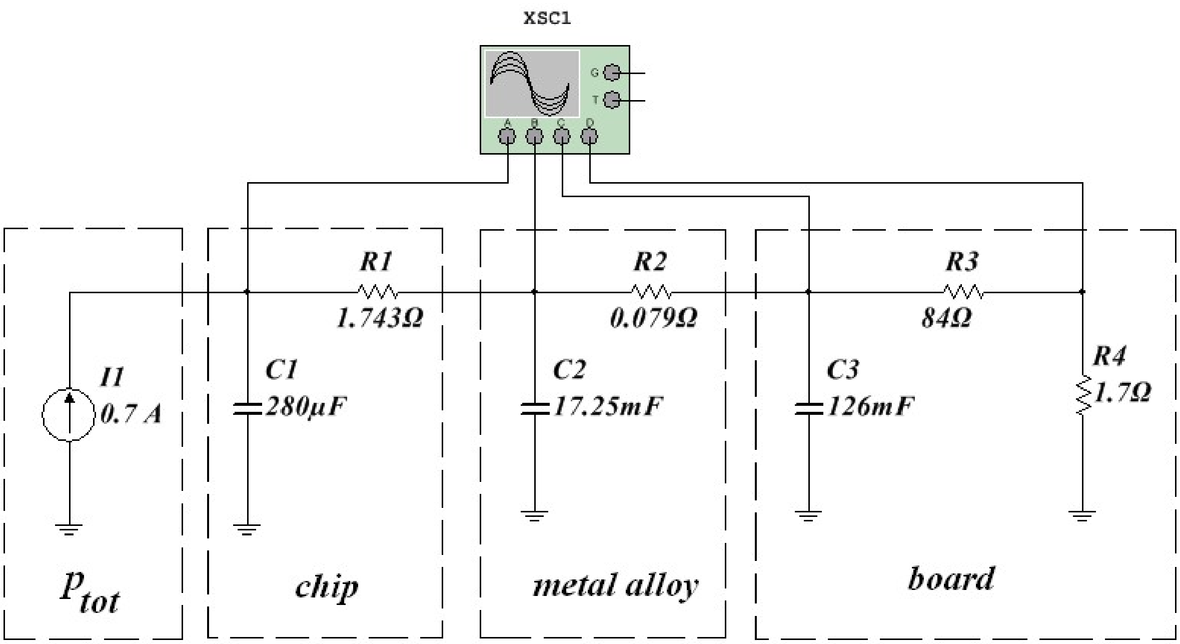

Fig.3. LED heat model in Multisim.

Figure 3 shows that a constant current source, which is the analog of the electrical loss power, released on the LED, is at the input of the circuit. The value of this power is 0.7 W, taking into account the efficiency of the LED, equal to 30%. Further there are RC-circuits in the model, which are the analogues of a crystal, a metal substrate and a printed circuit board, respectively. The values of resistors and capacitors in the developed model were calculated as follows.

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

The dimensions of the copper substrate are the following ones: height - 0.4 mm, diameter - 4 mm. The specific thermal conductivity of copper makes 401 W/m·K, the specific heat is 385 J/g·ºC, the density is 8.92 g/cm3. Substituting these values into the formulas (1) and (2), we obtain the following values of the thermal resistance for the metal substrate-printed circuit board and the heat capacity of the copper substrate: R2 = 0.079 ºC/W and C2 = 17.25 mJ/ºC.

The dimensions of the printed circuit board section, made of glass-cloth, which participates in the heat exchange process are equal: height - 1.2 mm, diameter - 7 mm. The specific thermal conductivity of the glass-textolite is 0.37 W/m·K, the specific heat is 1470 J/g·ºC, the density is 0.185 g/cm3. Substituting these values into the formulas (1) and (2), we obtain the following values of the thermal resistance for the printed circuit board and environment and the heat capacity of the printed circuit board: R3 = 85.7 °C/W and C3 = 126 mJ/°C.

Thus, the main components of the thermal model have been calculated. The value of the temperature for each element of the structure can be measured with the oscilloscope XSC1, since the voltage is the equivalent of temperature.

3. RESULTS

The developed model allows to study various thermal modes of a light-emitting diode work, to carry out the modeling at various electric modes of operation. This feature of the model is very actual in the modeling of operating modes, close to real ones. Under real operating conditions, the values of the power released in the crystals of the individual LEDs of the luminaire are different due to the presence of the technological spread in the values of parameters and characteristics. Such a variation in power values leads to the overheating of LEDs and their failure, which significantly reduces the life of a lamp as a whole. The research of such a problem is very important, because at present many manufacturers of LED equipment do not know about it. The created model makes it possible to study similar processes occurring in a luminaire.

In order to verify the working capacity of the developed model, we will simulate the thermal operating conditions of the LED at different values of power emitted in its crystal. Figure 4 shows the time dependences of LED crystal temperature at different values of power emitted in it: p_1 = 1 W; P_2 = 0.7 W; P_3 = 0.5W. Taking into account the efficiency of 30% in the nominal mode of operation the power value emitted in the LED crystal is 0.7 W. The initial temperature of the crystal is 20 °C.

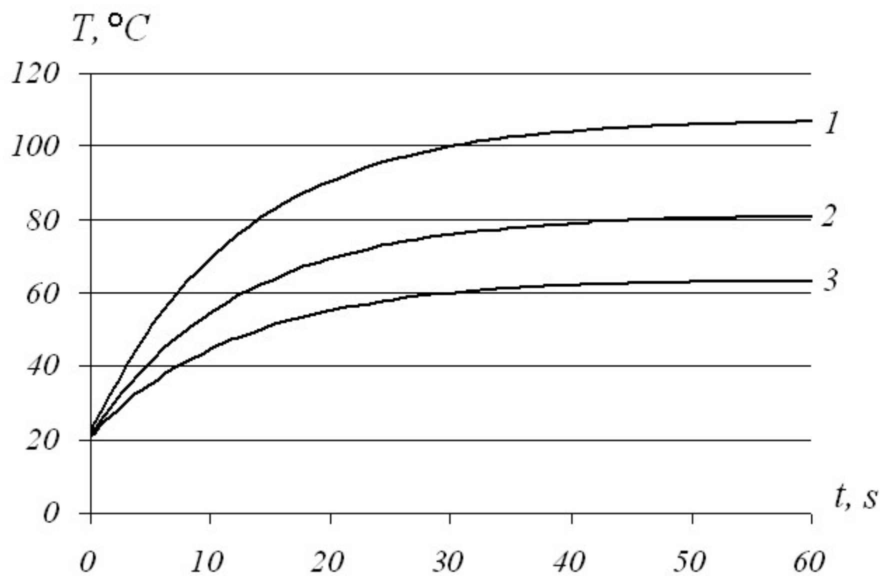

Fig.4. Time dependences of LED crystal temperature at different values of power emitted in it: 1 — p_1=1 W; 2 — p_2=0,7 W; 3 — p_3=0,5 W.

Figure 4 shows that in the nominal operating mode, when the crystal emits the power of 0.7 W, the temperature of the crystal in a steady state is 81 °C, which corresponds to the operating temperature of the LED. With the power of 0.5 W, the crystal temperature in a steady state is 63 °C, with the power of 1 W it makes 107 °C. The obtained results testify to the adequacy of the developed model.

The manufacturers of modern LED light sources are constantly trying to find an optimal version of a cooling system for various lamps and luminaires. To do this, they need to conduct a detailed analysis of the thermal processes occurring in a luminaire with different approaches to LEDs cooling. In some cases, cooling is sufficient, which is performed due to the heat dissipation by a printed circuit board on which LEDs are placed. In other cases, it is necessary to install metal radiators on LEDs, which ensure the nominal thermal mode of their operation. In order to choose an optimal cooling for an LED lamp, it is necessary to conduct the study of all possible electrical and thermal modes of its operation at different approaches to LED cooling. A developed thermal model allows to conduct similar studies. As a demonstration example, the thermal mode of the selected LED was simulated for various cooling of its crystal and the power released in it, equal to 1 W and exceeding the nominal value. The cases without additional cooling were considered, and the heat dissipates the case of the LED. Besides, the cases are considered where the heat is dissipated by a printed circuit board and a standard aluminum radiator. Figure 5 shows the time dependences of the crystal temperature for various cooling methods.

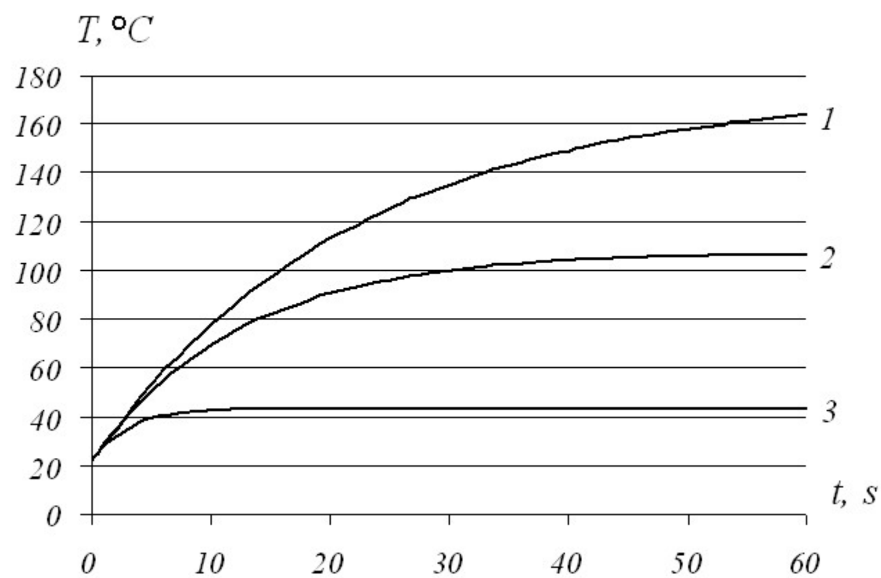

Fig.5. Time dependences of crystal temperature for various cooling methods: 1 - without additional cooling; 2 - cooling by a printed circuit board; 3 - cooling by the radiator.

Figure 5 shows that the most efficient cooling is provided, naturally, by the use of a radiator. The crystal temperature is 43 °C in steady state. In some cases, it is enough to cool with a printed circuit board, for example, when a smaller power is released in a crystal, or if a glass cloth metallized on both sides is used for better heat dissipation from a LED. If no cooling takes place, the temperature of the crystal reaches the value of 164 °C in 1 min. and continues to grow. Such a mode of operation will lead to the failure of a LED.

4. DISCUSSION

The thermal model of a light-emitting diode was developed, which makes it possible to study various electrical and thermal processes that occur both in individual LEDs and in LED lamps and luminaires. The results of the simulation performed confirmed the adequacy of the created thermal model and showed the possible areas of its application.

The thermal model allows to study the thermal modes of light-emitting diode operation at various electric modes of their work within a fixture that opens new opportunities for developers of similar production. As compared with existing analogues, the developed model has considerable flexibility and the ability to change input data quickly, which is necessary to model a large volume of their various combinations.

Besides, the thermal model has the ability to specify the parameters of LED design and take them into account during thermal process modeling. We can examine in detail the processes taking place in each element of a LED design and on their boundaries.

The ability to simulate with different approaches of LED cooling allows to select the optimum coolers and to calculate them to provide the most favorable thermal conditions inside a luminaire for the development of LED lamps and luminaires.

5. CONCLUSIONS

The developed thermal model makes the part of the electric thermal LED model, which will become the basis for a LED lamp model creation. The main distinctive feature of the created models should be the simplicity and the easiness of reconfiguration. The main task of the created models is the modeling of dynamic electric and thermal modes of operation for LED lamps and fixtures. It is planned to create a universal methodology to develop similar models for various LED lamps and luminaries in order to simplify the process of their design and to increase the reliability of LED products. The solution of this task will allow to provide favorable operating conditions for individual light-emitting diodes in a luminaire structure and significantly reduce the number of their failures. The creation of such LED light sources will contribute to the development of LED technologies and their application in many areas of industry and national economy.

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