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Investigation of the Heat Transfer in Radiators for LED Light Sources Using Thermography and Numerical Modeling

Abstract

Light-emitting diodes – LED, appeared on the market in the 60s of the last century, and today it is the fastest developing lighting technology. Due to high heat flux on the small surface of the individual diodes, problems related to the light source cooling become to be one of the basic ones. The paper presents results of the thermographic and numerical analyses of the chosen design of the LED lamp radiator. Experimental and computational data have been compared and discussed.

Keywords: LED, radiators, thermography, numerical modelling.

1. Introduction

Currently, the light emitting diodes (LED) are becoming more and more popular in households, public buildings and industry. The LED technology is characterized by the most dynamic development in the lighting market. In case of the mass production, in the last 10 years the luminous efficacy of the LED has increased from a few to over one hundred lm/W. Moreover, the LED characterized by the luminous efficacy on the level of 300 lm/W are now available (laboratory tests are currently being conducted) [1].

The efficiency of LED achieves more than 40%, what is much more than in case of the classic bulbs (usually less than 10%), or even compact fluorescent lamps. Among the other advantages of the LED we have to list [2, 3]:

- small size in comparison to other types of the light sources,
- high durability and robustness,
- low power consumption,
- ease of coupling with the integrated circuits, due to the low operating voltage.

The features mentioned above make the LED light sources appropriate solution for the all significant commercial applications, such as lighting of the households, automotive lighting, street lighting, light decorations, even medicine [4].

Principle of the operation of LEDs is based on the electroluminescence, which occurs in the p-n junction, through the electrons excitation, what is realized inter alia by applying the external electric field. Despite the completely different principles of operation than in classic bulbs, many popular types of the LED lamps are produced in casings resembling the shape of the bulb. However, it has to be noted that due to the specific construction of the source luminous intensity curve has a different shape in case of using in classic luminaires [4].

2. Studies of the impact of the temperature on the LED operation parameters

Due to the principle of the LEDs operation, except the light, a high amount of the heat is generated during the lighting process.

According to the results presented in [5], temperature of the LED lamps casings is just insignificantly related to the voltage of the power supply and lower than 70 - 80°C. The authors argue that the increase of the temperature of such devices is strongly dependent on the operation of the internal elements (increase of the power in the power supply system).

Authors of [6] have compared LED lamps from four manufacturers, stressed at room and high temperature. It was found that the long-term stress causes a change of the chromatic properties of the lamps and that the LED driver aging causes a reduction of the output optical power, or a complete failure. Proper thermal management and heat dissipation reduce the degradation rate [6].

a) b)

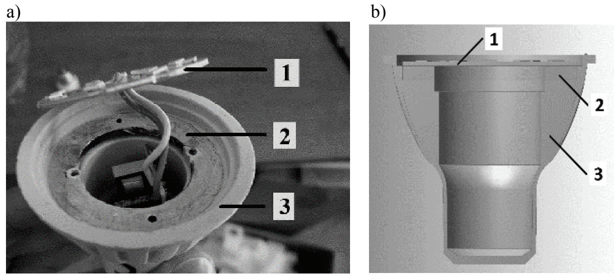

Fig. 1. Design elements of the analysed LED lamp: a) dismantled LED lamp, b) the symmetry plane of the CAD geometry. 1 - The mount with the LED diodes, 2 - aluminium ring, 3 - body of the lamp made of plastic

Because of impact of the diodes warming on the parameters of the lamps operation, heat dissipation from such elements is a significant problem.

A large part of the heat generated during the operation of LEDs is transferred through the material on which diodes are fixed (Fig. 1).

To provide the efficient heat removal from the diodes and consequently from the base material, the aluminium ring is applied, as shown in the Figure 1. Moreover, to increase the heat exchange with the ambient, the ribs on the perimeter of the lamp body are applied.

The excessive increase of the temperature of the diodes and heating of the lamp casing results in the luminous flux reduction, deformities and aging of the materials, as well as problems with the electrical contacts of the diodes, damages of electronics and other.

To provide optimal heat dissipation from the body of the LED lamp, it is necessary to arrange individual diodes in appropriate points. Equally important issue is design of the radiator, which has to provide efficient thermal convection.

Moreover, the key to efficient thermal management of device is design using software for thermal analysis and dedicated measurement methods.

From the temperature distribution point of view, it is reasonable to apply the thermographic analysis in the research of the LED lamps. The method gives a result in useful form of the spatial diagrams. On the other hand, it is possible to get the results only for the surface of the device. Mounting any sensors in the material of lamp is inadvisable, due to the impact of the sensor on the heat transfer. Accordingly, it is reasonable to consider numerical modelling, as a supporting tool in studies of the heat dissipation in the LED lamps, what can be useful on the stage of the development and optimization of the product.

Analysis of the phenomena related to the heat transfer in the LED material can also be performed using the advanced software. Currently, a wide range of the programs based inter alia on CFD (Computational Fluid Dynamics) is available to conduct this type of studies. Numerical models allow the performance of complex simulations, related to the fluid flows, but also the heat transfer in solid bodies. However, such a method requires an appropriate model, which is not always possible in case of the LEDs, due to lack of the information about the heat transfer occurring at the interface between materials, so results of the computation can be inaccurate. Due to the fact mentioned above, experimental methods are still important and have to be applied in parallel to the numerical analyses.

An opposite example of the application of the CFD in studies of the relation between the shape of the LED lamp body and efficiency of heat dissipation is described in [7]. In the paper numerical analysis was carried out for four types of radiators. Heat dissipation efficiency was found to be higher for the use of ribs characterized by lesser thickness and in case of their increased number. This is due to a larger contact surface with the environment.

3. Description of the measurement stand and the experiment

To allow performance of the experiment using IR camera, without significant impact of factors interfering with the measurement, the test stand has been constructed as shown in the Figures 2 and 3. To avoid the impact of the light flux on the result of measurement, wooden barrier covered by the reflective surface (from the site of the light source) has been mounted on the steel profiles construction.

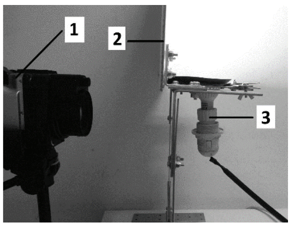

Fig. 2. General view of the test stand applied in the experiment using thermographic camera: 1 - thermographic camera, 2 - barrier on the rack, 3 - lamp holder

The rack has been equipped with the clamp (Fig. 3), to provide the possibility of connection of various types of LED lamps. During the experiment, the lens of thermographic camera were placed opposite to the LED lamp body, to allow the analysis of the side surface of considered light source.

The NEC Thermo Tracer H2640 infrared camera has been applied for the analysis. The device is equipped with the 640×480 pixels matrix and it is characterized by the thermal sensitivity 0,03 K (in 30°C ambient temperature).

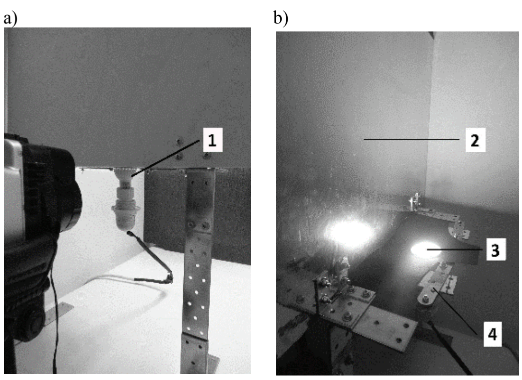

Fig. 3. The test stand details: a) from the camera point of view, b) from the light source side. 1 - Body of the LED lamp, 2 - reflective surface, 3 - top part of the lamp with the diodes emitting light, 4 - clamp

Measurement of the temperature distribution has been carried out for 30 minutes.

4. Preparation of the numerical model of the LED lamp

The commercial tool ANSYS WORKBENCH 15 has been applied to develop numerical model of the heat transfer in the LED lamp materials. Spatial geometry with required simplifications has been designed using the Autodesk Inventor 2015 software and exported to the DesignModeler module. In the mentioned tool, the symmetry plane of the geometry has been defined and domain of the air inside the lamp has been determined.

Discretization of the computational domains was carried out in ANSYS Meshing tool. Result of generation of the computational grid is presented in Figure 4.

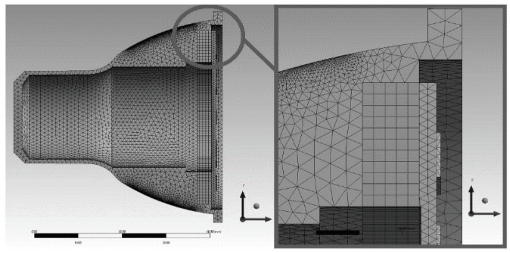

Fig. 4. Results of the computational domains discretization

Due to a complicated shape of the lamp body, it was necessary to use an automatic method of the grid generation for the most of the domains. In regular parts of the domain, such as the aluminium ring, the "multizone" method of discretization has been applied, to increase the number of hexagonal mesh elements in the structure (Fig. 4. b). Total number of the grid elements was 1.6×10^6.

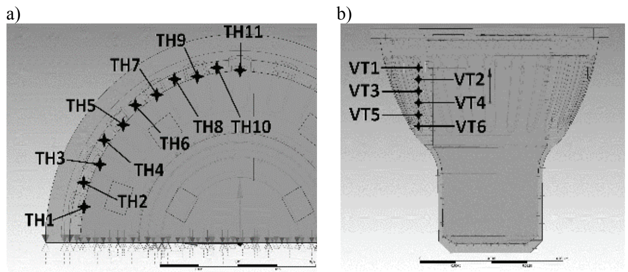

Fig. 5. Location of the temperature monitors set for the developed numerical model of the LED lamp: a) view from the top for the points arranged over the circumference, b) symmetry plane of the lamp - vertically arranged points

An accurate analysis of the heat transfer from the diodes through the material of the lamp body was possible by using so-called monitor points. The monitor points are defined in preprocessor by coordinates, expressions and type of variable, which is displayed. In the case of considered analysis, the monitor points were set using cylindrical coordinates (axial, radial and angular position) and were defined as the temperature monitors. Location of the monitor points is presented in Figure 5. Eleven points were arranged over the circumference of the top part of the lamp body (Fig. 5. a). Another six points were set vertically (Fig. 5. b).

A total of four domains were defined: Laminate (thin copper surface on the glass fibre) - for the material of the base for the diodes mounting, aluminium - for the material connecting the previous one and the body of lamp, PBT (Polybutylene terephthalate) - for the material of the lamp body. Based on the information obtained from the producer, important physical properties of mentioned above materials were determined, such as density, thermal conductivity, specific heat, molar mass, thermodynamic state and other.

The chosen properties of the PBT, which were applied in the model are listed in the Table 1.

Tab. 1. Basic properties of the PBT material used in developed numerical model

Parameter	unit	value
Density	$g\cdot cm^{-1}$	1.31
Specific heat	$J\cdot kg^{-1}\cdot K^{-1}$	2300
Thermal conductivity	$W\cdot m^{-1}\cdot K^{-1}$	0.21

Initial conditions were limited to setting the temperature of all computational domains, which equalled 298,15 K.

The external surface of the radiator was defined as a wall and on the current stage of the model development there was no domain surrounding the heat sink (for example to take into account different cases of air movement, ambient temperature changes etc.). In such case it was necessary to define parameter, which includes heat dissipation of the case. The basic parameter useful in such a case of simulation is a heat transfer coefficient. This may be a total heat transfer coefficient whose value is most desirable because of significant simplification of the computation process. The overall heat transfer coefficient of the surface describes a heat exchange by radiation and convection between the heating surface and the environment. However, for a detailed analysis of heat required transfer coefficient values of the surface by convection, and by radiation. The overall heat transfer coefficient should not be calculated as the sum of the coefficients resulting from the phenomena of radiation and convection. It is due to the fact that these parameters are based on different physical phenomena [8]. Total heat transfer coefficient was equal 10 $W \cdot m^{-2} \cdot K^{-1}$.

The inlet boundary condition was defined on the surface of the connection between the individual diodes and the laminate material - each area of the connection was individual heat source. The constant temperature 378,15 K was set for such boundary conditions.

It was decided that for the internal volume of the heat sink (area for the electronics placement) it is reasonable to define fluid domain. The air domain has been determined to take into account phenomena occurring in this section of the lamp body. Because the air domain has been defined just to improve the results of the computations in the laminate, aluminium and PBT, the *k*-epsilon model of turbulence was enough for the modelling of the air domain motion. Moreover, it was unnecessary to define the inflation layers (phenomena on the interface between internal wall of the body and air domain were not studied).

To provide the data transfer between each domains, set of the interfaces has been defined: laminate - aluminium, aluminium - BPT, laminate - air, aluminium - air and BPT - air.

The ANSYS CFX solver has been used to perform the computation process for developed numerical model. Numerical computation was carried out using transient mode for 30 minutes. The time step was 10 s.

5. Results of the experiment and the numerical simulations

The points of temperature measurement in accordance with the coordinates from the numerical model have been located on the diagrams, which are result of the thermographic analysis, using computer tools dedicated for the camera used.

Figure 6 presents the thermogram from the 30th minute of the test (end of experiment), including measured temperatures and values calculated by the model. Points marked by crosses as well as the line marked as 1 were generated after the experiment, using software dedicated for the camera used in measurement. Tools included in the software allow to check value of the temperature in marked points, lines and average value for chosen region. The "E" symbol in each description before value of the temperature is related with the results of experimental test, while the "S" symbol is devoted to the computational data.

Simplifications assumed for the model development and the simulation process have led to divergent the experimental and computational data. In each cases, difference is equal less than 2,5 K, so the agreement of test and model result is satisfying.

There is a number of factors which are difficult to define accurately, what results in differences between experimental and model results, such as warming up of the LED diodes, variability of the intensity of the thermal convection and radiation, heat exchange between interior of the device (space for the electronics) and ambient, as well as properties of the plastic used to produce the lamp body.

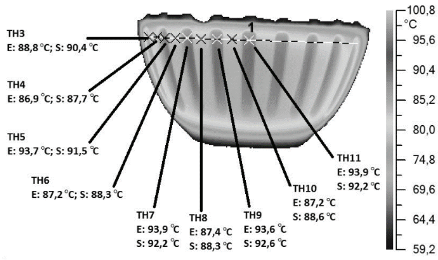

Fig. 6. Thermogram from the 30th minute of the experimental test. Points and the line, for which the temperature measurement has been conducted are visible

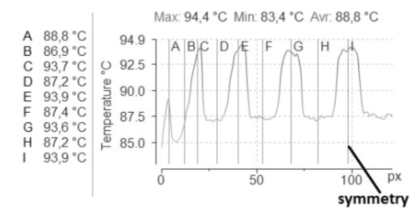

Fig. 7. Changes of the temperature along the line marked as 1 on the thermogram presented in Fig. 6

Fig. 7 shows the temperature distribution along the line, which is visible in Fig. 6. Points marked as A - I correspond to monitors TH3 - TH11. Due to the cylindrical geometry the monitors TH1 and TH2 are hidden and it was impossible to observe all the points corresponding with the temperature monitors (TH) from the model on the thermogram. The curve represents the horizontal distribution of the temperature between the ends of the set line. The temperature level on the surfaces in the grooves is relatively constant. Because of the intensive heat transfer from the PBT material to the ambient, the temperature variation along the ribs is dynamic. It has to be noted that differences in shape of individual peaks on the chart are partially related with the phenomenons occurring in the area of measurement, but it is also effect of various angle of the measured surface to the lens of the camera.

In the postprocessor of the numerical model, different shades of colors on the generated planes, cross sections and surfaces, correspond to different values of displayed variables. In this connection, in case of the performed analysis, it was possible to make a direct comparison of the thermograms and results of the simulation.

Figure 8 shows the screen from the CFX post processor, with visible temperature distribution on the external surface of the lamp body (a) as well as symmetry plane (b).

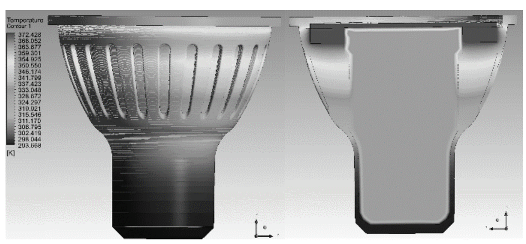

Fig. 8. Example result of the computation - screen from the postprocessor with displayed temperature distribution: left - the external surface of the LED lamp body, right - the symmetry plane of the LED lamp body

The temperature changes along the device can be visible better because of the lack of interferences. The advantage of the numerical model in comparison with the thermographic measurement is that it is possible to observe phenomena occurring inside the material.

Thanks to the application of the transient analysis it was possible to monitor dynamics of the temperature variation in the set of points VT1 - VT6 (Fig. 9) in time of the simulation (30 minutes). The chart shows impact of the heat sources located in points of the LED diodes mounting on a dynamic of the temperature changes in the

PBT material. It was possible to determine the time of the stabilisation of the LED lamp operation conditions.

The highest curve in Figure 9 corresponds to the region in the device nearest to the heat sources and the temperature in point VT1 reaches ~370 K. Value is just slightly higher than in case of the points presented in Fig. 6 due to location of the VT monitor points on the symmetry plane of the heat sink body. Of course the highest temperature of the PBT material in the simulation is nearly equal the value set for the inlet boundary conditions. Temperature rise for the rest of the monitor points decreases in proportion as the distance from the top of the lamp and the values are stable at all points after about 30 minutes. Time of the temperature stabilization matches the value recorded during the thermographic measurement.

The rate of heating and the final level of the temperature of the individual parts, observed by the monitor points, depend on the shape of device. In the bottom part, the lamp body is much thinner, what results in better heat dissipation and lower temperature. It has to be noted, that during simulation heat flux from the internal electronic elements was not taken into account.

Based on the comparison between the experimental and computational data presented in Fig. 6 it was concluded that due to the acceptable agreement of measurement and simulation it is reasonable to consider numerical modelling as an essential tool to support the process of studies and development of the LED lamps.

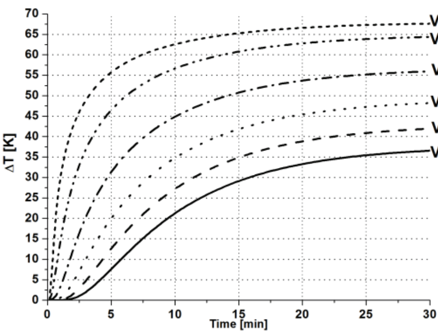

Fig. 9. Dynamics of the temperature variation in the monitor points VT1 - VT6 set in the vertical axis of the lamp body material

6. Conclusions

High temperature of the LED lamps, which is result of the diodes operation has negative impact on the most important exploitation parameters of the device, including luminous flux, light quality and robustness of the lamp. It is reasonable to use the thermographic camera and the numerical simulations in the process of development and optimization of the LED lamps. Implementation of the optimization recommendations mentioned above will be subject of the next stage of the experimental and numerical studies and will be presented in next articles.

Transient numerical analyses give set of the valuable information about the process of the heat transfer during operation of the lamp, without the need for a number of experimental measurements and construction of advanced test stands. The application of the numerical simulations in analyses of the new-designed LED light sources requires the validation of the models using the existing devices, which can be carried out inter alia through the thermographic measurements. In case of the studies performed, satisfying degree of agreement between the results of the experiment and computation has been achieved.

Based on the result it was decided that the works will be continued using the advanced test stand, equipped with the system of the forced air circulation, control and data acquisition system connected with set of the temperature measurers and improved barriers, preventing the interference of the light flux with the thermographic measurement. The numerical model has to be expanded by the additional conditions, such as the impact of top cover on the lamp temperature, second heat flux, which results from the operation of the electrical circuits, as well as the movement of air surrounding analysed device.

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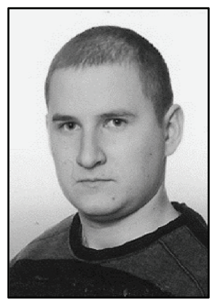

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