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THE INFLUENCE OF THE LED LUMINAIRES ELECTRICAL PARAMETERS ON THEIR CORRELATED COLOUR TEMPERATURE DURING OPERATION MODE

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ABSTRACT

The article describes the results of comprehensive study aiming at increase of quality of LED luminaires and definition of the nature of changes in their correlated colour temperature (CCT) in the course of operation. Dependences of CCT of LED luminaires with remote and close location of phosphor for 10 thousand hours of operation in different electric modes were obtained; the results of comparison between the initial and final radiation spectra of the luminaires are presented; using mathematical statistics methods, variation of luminaire CCT over the service period claimed by the manufacturer is forecast; the least favourable electric operation modes with the highest CCT variation observed are defined.

The obtained results have confirmed availability of the problem of variation of CCT of LED luminaires during their operation. Possible way of its resolution is application of more qualitative and therefore expensive LEDs with close proximity of phosphor or LEDs with remote phosphor.

The article may be interesting both for manufacturers and consumers of LED light sources and lighting devices using them.

Keywords: LED luminaire, electric mode of operation, supply current, radiation spectrum, radiant flux, correlated colour temperature

1. INTRODUCTION

The problems of LED lighting development in Russia are primarily caused by lack of relevant regulatory framework, which allows unfair manufacturers create lighting products of poor quality and confuse consumers by claiming, for instance, insubstantially long service life for LED lighting devices (LD), about (70–100) thousand hours [1, 2].

In 2018, the standard of the Association of LED and LED-Based Systems Manufacturers became effective [3]. It united general requirements to LDs, requirements to their photometric, colorimetric, and electric parameters, electromagnetic compatibility, safety, reliability and warranty liabilities. According to the standard, one of the standardised colorimetric parameters of LDs is correlated colour temperature (CCT) which is calculated based on a LD radiation spectrum [4].

The value of CCT should comply with the range of permissible deviations from the corresponding rated value of CCT [5] which shall be declared by manufacturers in technical specifications and operational documentation with specification of the size of areas of possible deviations in MacAdam Ellipses [3].

At present, manufacturers of LED-based luminaires have no information on the nature of changes of CCT of these devices in the course of their operation due to degrading of LEDs with consideration

Table 1. Technical Specifications of the Tested Luminaires

№	Parameter	Manufacturer 1	Manufacturer 2
1	Rated power, W	24	19
2	Rated luminous flux, lm	3750	2580
3	Rated LED current as per the data sheet, mA	350	350
4	Rated current of LEDs in the luminaire, mA	350	260
5	CCT (K)	3000	4000
6	Service life, thousand hours	> 70	90

of their electric and thermal operation modes [6, 7]. Therefore, it is impossible to precisely evaluate service life of LED-based luminaires as manufacturers do not know in what time CCT of a luminaire will go beyond the specified limits even in the nominal operation mode [8]. With that, LEDs in luminaires often operate in electric and thermal modes which are different from the nominal one, therefore studies of their radiation spectra and their temporary changes in different operation modes remain a relevant problem.

In view of this, the goal of the work was to increase quality of LED-based luminaires by defining the nature of changes of CCT during their operation with consideration of the electric operation mode. To reach this goal, the following objectives were set:

– To obtain time dependences of luminaire CCT over 10 thousand hours of operation in different electric modes of operation;

– To compare radiation spectra of luminaires in the beginning with that after 10 thousand hours of operation;

– To forecast variation of luminaire CCT over the service life claimed by manufacturers using methods of mathematical statistics;

– To define electric modes of operation which are the least favourable for luminaires and demonstrate the highest variation of CCT over the course of operation.

It was assumed that the results of the study would allow manufacturers of LEDs and LED-based luminaires to understand the causes of variation of radiation spectra and CCT of these products in the course of operation and to take relevant measures in order to increase their service life [9].

2. METHODS

The study of time dependence of radiation spectrum and CCT was conducted using a series of LED-based luminaires by two Russian manufacturers in different electric modes of their operation. For ethical reasons, the names of manufacturers are not mentioned in the article. The luminaires by Manufacturer 1 are based on LED with remote phosphor, which, according to the manufacturer's data, allows them to keep its characteristics and parameter values close to rated ones over the entire service life. In the luminaires by the Manufacturer 2, LEDs with close location of phosphor (the most common type of LEDs) are used. Table 1 contains major technical specifications of the said luminaires.

The photo-colorimetric installation (approval certificate of measuring instruments No. RU.E.37. 003.A NG 64752) was designed to measure luminous flux, CCT, and chromaticity coordinates in *x, y, z* (1931), *u, v* (1960) and *u,'v'* (1976) systems and used for measurements of radiation spectra and CCT. The operation principle of the installation is based on definition of the values of radiometric, photometric and colorimetric values by measuring absolute spectral radiant flux within the wavelength range of (360–1100) nm. CCT was defined automatically using software supplied with the installation. The latter consists of the integrating sphere *OL IS-7600*, the multi-channel spectrometer *OL 770 VIS/NIR* and the auxiliary lamp *A180* with the power supply source *OL 410–200*. The aluminium integrating sphere has diameter of 1950 mm and consists of two separate hemispheres, two output ports, lamp port (auxiliary) and the internal fixture of the lamp holder. Both hemispheres can be easily disconnected (for simplification of installation and replacement of the lamp or fixture parts). The sphere diameter allows us to measure luminaires with length of up to 1800 mm and maximum luminous flux of 200 klm. One of the output ports is connected with the entrance slit of the spectrometer using a fibre-optic cable. The light incident on the inner wall of the sphere gets into this slit via the

Table 2. Results of Measurements of CCT of the Luminaires in the Nominal Operation Mode

	Luminaire No. 1	Luminaire No. 2	Luminaire No. 3	Luminaire No. 4
CCT, K (Manufacturer 1)	3084	3066	3082	3100
CCT, K (Manufacturer 2)	4195	4230	4235	4198

Table 3. Ranges of Maximum Deviation of CCT Values for Corresponding Nominal Values

Nominal value of CCT, K	Central value of CCT and range of permissible deviations for 7-step MacAdam Ellipse, K	Central value of CCT and range of permissible deviations for 4-step MacAdam Ellipse, K
3000	3045 ± 175	3045 ± 100
4000	3985 ± 275	3985 ± 154

fibre-optic cable. Then it falls on the concave diffraction grid, which separates the light into monochromatic components and focuses it on the CCD matrix. After the light is reflected from the grid, each its monochromatic component falls on the section of the CCD matrix allocated for it. In front of the output hole of the sphere and in front of the auxiliary lamp inside the installation, protective screens are installed, which prevent escape of any direct radiation.

The following operating modes of the luminaires were selected for the study.

Mode 1

Nominal mode with LED current in the luminaire equal to the nominal one: 350 mA (Manufacturer 1) or 260 mA (Manufacturer 2) claimed by the manufacturer, and current ripple factor does not exceed 1 %.

Mode 2

Overload current mode with LED current in the luminaire, exceeding the nominal one. In luminaires by the Manufacturer 1, this current was 10 % lower than nominal one and equal to 390 mA (Table 1). Since nominal LED current in the luminaire by the Manufacturer 2 (260 mA) is less than rated (nominal) current for these LEDs (350 mA), it was decided to select the specified rated current as current overload of LED in the luminaire (Table 1). Current ripple factor of the luminaires by both manufacturers does not exceed 1 %.

Mode 3

The mode in which LED current in the luminaire is equal to nominal LED current and the current ripple factor is equal to 10 %. Ripple frequency in the modes 3 and 4 is 50 kHz.

Mode 4

The mode in which LED current in the luminaire is equal to nominal LED current and the current ripple factor is equal to 40 %.

The required supply currents of LED matrix of the luminaires were set by means of adjustable control devices (drivers) manufactured by the Argos-Trade company (Saint Petersburg) which allow to adjust output current from 240 mA to 390 mA [10] and necessary current ripple factors by changing and selecting output inductance of CD using the time dependence of current on the screen of the digital oscilloscope.

3. RESULTS

For the experiment, two lots each consisting of four luminaires by each manufacturer were selected. First, luminaire CCT values were measured in the nominal operation mode, Table 2.

The ranges of maximum deviation of CCT values from its corresponding nominal value as per the standard [3] are shown in Table 3. Tables 2 and 3 demonstrate that for the new luminaires (by the Manufacturer 1) the CCT variations comply with the requirements of the standard [3]. The deviation of CCT values of new luminaires (by the Manufacturer 2) is much higher and goes beyond permissible deviations for 4-step zones as per Table 3 (the upper limit of 4139 K).

The variations of radiation spectrum and CCT of the said luminaires over 10 thousand hours of operation were measured each 2 thousand hours. Time spent for measurements was not included in calculation of total operation time of the luminaires. Us-

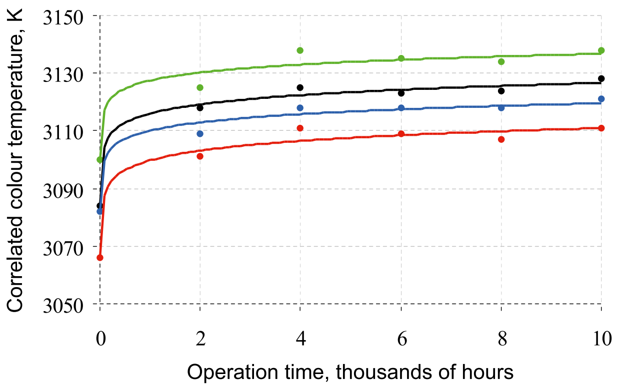

Fig. 1. Time dependences of CCT of the luminaires by the Manufacturer 1 in different operation modes: mode 1 (black); mode 2 (red); mode 3 (blue); mode 4 (green)

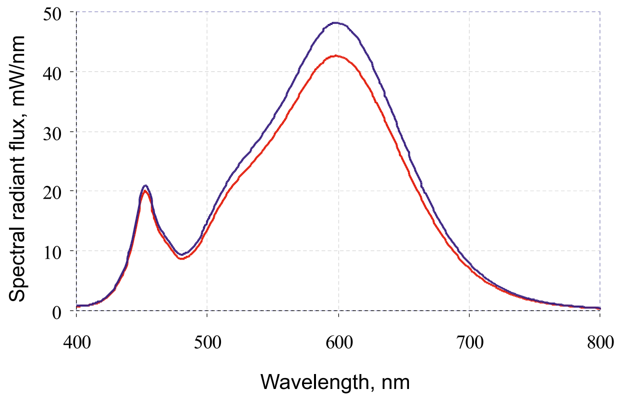

Fig. 2. Radiation spectra of the luminaire by the Manufacturer 1: initial (blue) and after 10 thousand hours of operation in mode 2 (red)

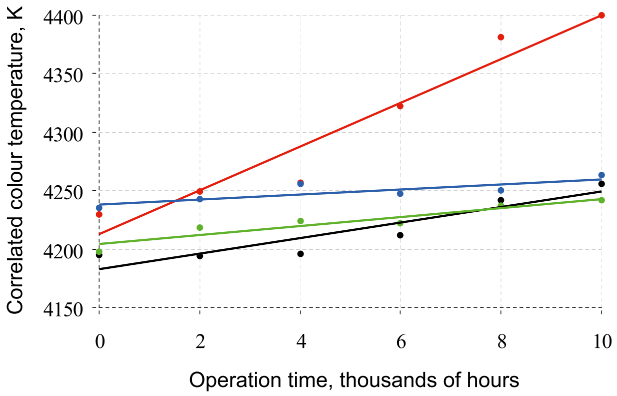

Fig. 3. Time dependences of CCT of the luminaires by the Manufacturer 2 in different operation modes: mode 1 (black); mode 2 (red); mode 3 (blue); mode 4 (green)

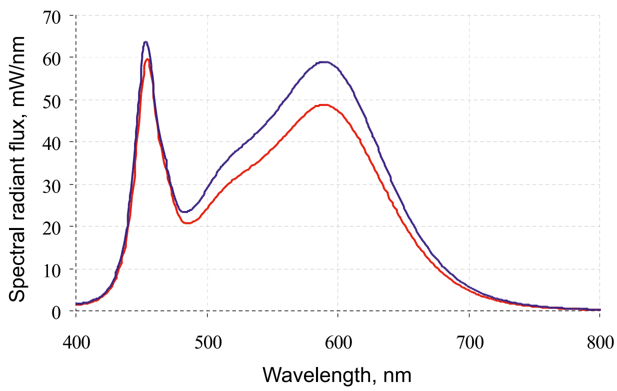

Fig. 4. Radiation spectra of the luminaire by the Manufacturer 2: initial (blue) and after 10 thousand hours of operation in mode 2 (red)

ing Table 2, corresponding operation mode was set for each luminaire.

Fig. 1 shows time dependences of CCT of the luminaires by the Manufacturer 1 in different operation modes. Optimal approximations (logarithmic) of these dependences, CCT, K on operation time t (thousand hours) obtained using *MS Excel* are as follows:

CCT = 4.5998·ln(t) + 3115.9 (mode 1); CCT = 4.8382·ln(t) + 3099.7 (mode 2);

CCT = 4.1064·ln(t) + 3110 (mode 3); CCT = 4.0043·ln(t) + 3127.4 (mode 4).

Fig. 1 shows that the rate of increase in CCT of the luminaires by the Manufacturer 1 is roughly the same in different modes of operation. After 10 thousand hours of operation, the values of CCT did not go beyond the ranges of permissible deviations for 4-step and 7-step zones (Table 3), the upper limits of which are equal to 3145 K and 3220 K respectively.

The highest variation of CCT was observed in a luminaire by the Manufacturer 2 operating in the Mode 2 (current overload) and the change of its radiation spectrum after 10 thousand hours of operation is shown in Fig. 2. The figure shows that peak spectral radiant flux at wavelength of about 600 nm corresponding to orange-red light has lowered by 6 mW/nm over this period, while the peak at wavelength of about 450 nm (blue light) has not changed much. This pattern explains that increase in CCT over time is related to increase in the share of the blue component in the radiation spectrum of the luminaire.

The results of tests of the luminaires by the Manufacturer 2 in different modes of their operation are shown in Fig. 3. Optimal approximations (linear) of these dependences also obtained using *MS Excel* are as follows:

CCT = 6.0359·t + 4184 (mode 1); CCT = 16.978·t + 4216.9 (mode 2);

CCT = 1.807·t + 4239.5 (mode 3); CCT = 3.4238·t + 4205.4 (mode 4).

The nature of variation of CCT over 10 thousand hours of operation of the luminaires by the Manu-

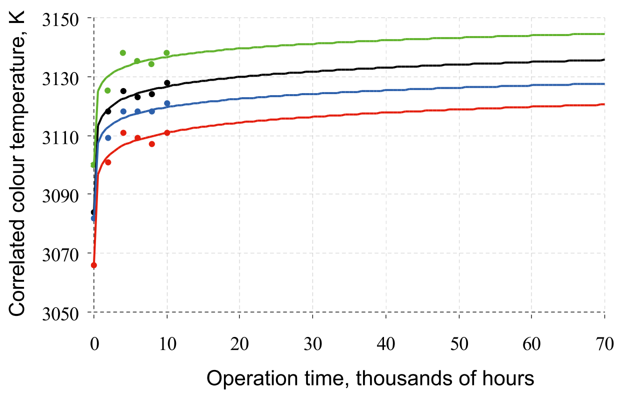

Fig. 5. Time dependence of CCT of the luminaires by the Manufacturer 1 over 70 thousand hours of their operation: mode 1 (black); mode 2 (red); mode 3 (blue); mode 4 (green)

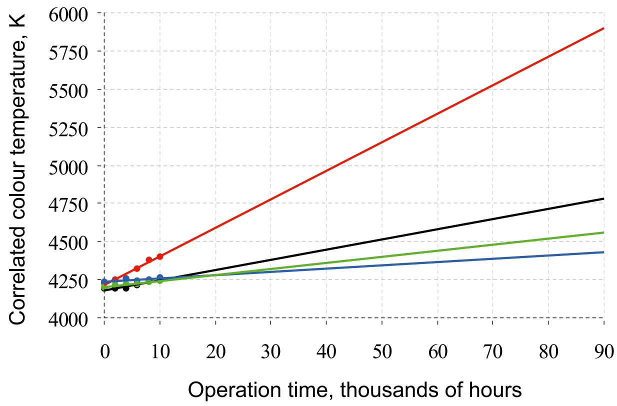

Fig. 6. Time dependence of CCT of the luminaires by the Manufacturer 2 over 90 thousand hours of their operation: mode 1 (black); mode 2 (red); mode 3 (blue); mode 4 (green)

facturer 2 is the same for all operation modes. The highest CCT increase rate was observed in mode 2.

CCT in this mode increased by 170 K and reached 4400 K, which is much higher than the upper limits of the permissible deviations for the 4-step and 7-step MacAdam Ellipses (Table 3).

The change of radiation spectrum of this luminaire operated in the mode 2 after 10 thousand hours of operation is shown in Fig. 4. In the peak area at wavelength of 590 nm, the decrease in spectral radiant flux was equal to value 10 mW/nm, while in the peak region at wavelength of 450 nm this value decreased by 4 mW/nm. Like in the case of the luminaire by the Manufacturer 1, this explains the increase in CCT in that case.

It was interesting to evaluate the limits of CCT variation of the said luminaires over the service life claimed by their manufacturers (Table 1). Given the duration of these periods, the methods of mathematical forecasting were applied based on the results of luminaire tests over 10 thousand hours. Possibility to forecast based on a rather short period of time is conditioned by the fact that, after 10 thousand hours of continuous operation, parameters and characteristics of LED start changing significantly due to degradation processes in the phosphor and the crystal, which is usually mentioned in data sheets of any LED or LED-based LD. Therefore, while forecasting on the basis of the first 10 thousand hours of operation of the luminaires, we consider the most favourable option, and if the luminaires do not comply with the specified requirements [3] in these conditions, then it is obvious that the claimed service life of the luminaires (Table 1) will not be real.

One of the most popular types of graphic forecasting (implemented in *MS Excel*) was used: extrapolation by building a trend line. This type of forecasting is based on building of a graph of the considered dependence using tabular data consisting of arguments and values of the function, superimposition of the trend line, and selection of one of the six types of approximation.

The results of forecasting of the time dependence of CCT of the luminaires by the Manufacturer 1 are presented in Fig. 5, which shows that “final” CCT values of the luminaires did not go beyond the ranges of permissible deviations specified in Table 3 for the 4-step and 7-step MacAdam Ellipses (the upper limits are equal to 3145 K and 3220 K respectively). Maximum CCT of 3143 K is shown by the luminaire operating in mode 4. The highest CCT variation, 50 K, is observed for the luminaire operating in mode 2.

The results of forecasting the time dependence of CCT of the luminaires by the manufacturer 2 are presented in Fig. 6, which shows that CCT values of each test mode goes significantly beyond the ranges of permissible deviations specified in Table 3 for the 4-step and 7-step MacAdam Ellipses (the upper limits are equal to 4139 K and 4260 K respectively). The maximum CCT variation of 1650 K, with which it reached 5880 K, is found in test mode 2.

4. CONCLUSION

Based on the conducted studies, the following conclusions may be drawn.

1. CCT of the luminaires by the Manufacturer 1 based on LEDs with remote phosphor did not ex-

ceed the ranges of permissible deviations as per the standard [3] in any test mode [3]. CCT of the luminaires by the Manufacturer 2 based on LEDs with close location of the phosphor significantly exceeds the upper limits of the ranges of permissible deviations [3] in each test mode. The reason of it is that in the LED with close location of phosphor, the latter, together with the crystal, suffers bigger thermal effect than the remote phosphor with corresponding crystal, and, therefore, they degrade and change CCT faster. The remote phosphor technology allowed us to solve this problem partially.

2. Resulting from degradation of phosphor and LED crystal, predominant decrease in the level of spectral radiant flux of LED-based luminaires over their operation within the wavelength range of (500–700) nm changes (increases) CCT of these products.

3. The highest variations of CCT of the luminaires by both manufacturers were observed in mode 2 (current overload), in which LEDs suffered thermal overloads that accelerated the degradation processes in the crystal and phosphor. However, in the luminaires by the Manufacturer 1, this mode did not causes fatal changes of CCT, while in the luminaires by the Manufacturer 2, CCT exceeded the limits of the ranges of permissible deviations already after 10 thousand hours of their operation. Therefore, the mode with supply current of LED higher than nominal current, which is often used by manufacturers to increase luminous flux of luminaires, is highly undesirable.

4. In terms of CCT variation rate of the luminaires by both manufacturers, modes 3 and 4 (with supply current ripple factors significantly higher than permissible values) are just slightly different from mode 1 (nominal).

5. A possible way to increase stability of CCT of luminaires in the course of operation is to use more qualitative (and hence expensive) LEDs with close location of phosphor or LEDs with remote phosphor.

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