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Super powerful LED luminaires with a high color rendering index for lighting systems with combined electric power supply

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Abstract. Considered in this paper are development and creation of high-power LED luminaires with high light efficiency and color rendering index (CRI). As light sources, there used are 6 powerful LED COB (Chip-on-Board) modules CreeCXA 2550, the radiation of which contains quasi-chromatic peaks in the spectral range 600…650 nm. It allows to provide CRI values higher than 92. Features of the improved compact construction of the luminaire with indicated COB modules have been presented. To ensure normal thermal regimes of LED COB modules, a small cooling system based on heat pipes has been created, the optimal dimensions of the structural elements of which have been determined by computer simulation. The results of modeling and experimental studies have shown that the developed and manufactured passive cooling system of LED COB modules provides operation temperature modes (up to 85 °C) of light-emitting crystals at the total electric power of COB modules up to 290 W and allows using the luminaires of this type in the systems of continuous artificial illumination with combined power supply. The efficiency of the developed cooling system at some angles to the horizon expands the scope of applying the illumination device.

Keywords: energy effective lighting, LED, color rendering index, air cooling, heat pipe.

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1. Introduction

The most efficient and durable light sources are light-emitting diodes [1–3]. Numerous studies [4–9], performed in the recent decade in the field of creating new semiconductor light-emitting structures, allowed to bring the efficiency of their separate experimental samples to the theoretical limit of light efficiency of artificial light sources [10]. Due to the high reliability and efficiency of modern organic [11–13] and inorganic [14–16] LEDs, they are widely used, in addition to illumination, in the constructions of displays [18], information boards [19] and indicators [20], providing unattainable for other technologies values of brightness, contrast and energy efficiency.

New technological solutions used to create modern high-power LEDs and LED COB (Chip-on-Board) modules [21] allow creation of high-power luminaires in which one [22] or several [23, 24] high-power LED light sources are used. At the same time, the areas of application of these high and ultra-high power luminaires require a combination of high reliability and manufacturability, low energy and material consumption, as well as a modern appearance in these constructions.

Wide implementation of semiconductor light sources leads to almost complete displacement of lighting systems based on light sources of other physical nature (incandescent lamps, discharge lamps), which requires creation of LED lighting systems for various functional purposes. At the same time, the desire to significantly increase the light efficiency of luminaires often leads to the use of LEDs with a low color rendering index (CRI) [25], which can negatively affect the perception of objects that are illuminated, such as exhibits in art galleries and museums, goods in supermarkets and shopping malls, shops of building materials and auto parts, special military facilities, *etc.*

To date, incandescent lamps are used to ensure high CRI values (higher than 90), but the efficiency of illumination devices based on them is tens of times lower than those with LED light sources, service life is hundreds of times shorter, and light distribution and spectral composition do not always meet the requirements to modern light sources. The need for light sources with high CRI requires from specialists in this field new design solutions for lighting systems that can provide the required technical and spectral parameters.

The problem of improving the quality of light in LED devices is solved mainly by using in light-emitting diodes the light-converting material (luminophor) [26–28] with high CRI and by providing appropriate operation temperature modes of light-emitting structures. The latter problem is especially important when using high-density LED arrays with high density of high-power LED chips on small areas [29], because modern LEDs, when operating in adverse temperature conditions, reduce their photometric parameters and change the spectral parameters [30, 31]. The need to ensure normal temperature modes of high-power LED sources requires the search for and development of new approaches to solving the problems of heat dissipation that appears during operation of luminaires.

To ensure the operation temperature modes of high-power LED sources, various cooling systems are used, they are based on radiators [32], thermoelectric coolers [33], piezoelectric fans [34], jet coolers [35], as well as cooling systems, in the design of which two-phase heat transfer devices are used – heat pipes [22–24, 36, 37]. All the existing cooling systems can be separated into two groups: active and passive.

Given that LED luminaires have a long service life, it is most appropriate to use passive cooling systems without using any active electromechanical devices and elements (pumps, fans, *etc*.). To ensure the operation temperature modes of high-power LEDs, in [38] there was developed construction of a new passive cooling system, which uses two-phase heat transfer devices – heat pipes installed by their heating zones in the areas of the luminaire with the highest concentration of heat flux.

The peculiarity of heat pipes is that their effective thermal conductivity is tens of times higher than the thermal conductivity of traditional metallic materials (such as copper, aluminum and their alloys) [39], so heat pipes are widely used as heat-conducting elements of cooling systems in computer [40–42] and rocket-space [43–45] technology. A significant advantage of using the cooling systems based on heat pipes in LED luminaires is low thermal resistance with low material consumption of the cooling system, which allows to ensure low temperature of LEDs and to increase their reliability [46–48].

Lowering the temperature of light-emitting crystals and increasing the reliability allow one to use heat pipes in continuous artificial lighting systems. Continuous artificial lighting systems require continuous power supply for their operation, which is often provided by the use of combined power supply systems [49, 50] used during the day for rooms with no natural insolation.

Under conditions of exclusively artificial lighting, in order to avoid errors in color perception and reduce human fatigue, lighting systems must simultaneously provide high values of both illuminance and CRI. The use of luminaires with high CRI allows one to provide comfortable lighting environment at lower absolute values of illumination [51].

The use of LED luminaires helps to improve the ecological state of the environment due to reducing energy consumption, which lowers the need for organic fuels. An additional resource to increase the environmental friendliness of lighting is the use of lighting systems with combining the power supply from the general power supply network and energy generated by solar panels.

The use of intelligent algorithms in these lighting systems is able to ensure high stability of light flux and continuity of the system regardless of the power source. The development and implementation of LED lighting systems with combined power supply allows reducing the load on the general power supply network, which is very important today against the background of the global energy crisis.

The tasks of this work are as follows: selection of LED light sources to create a powerful luminaire with high CRI for continuous lighting systems with combined power supply, for manufacturing an experimental sample of a luminaire with a passive cooling system based on heat pipes and for conducting experimental research of its electro-optical and thermal characteristics.

2. Selection of LED light sources and design features of the experimental sample of ultra-high power LED luminaire with high CRI and efficient cooling

2.1. Selection and study of parameters of LED light sources with high CRI

Development and creation of an ultra-high-power LED luminaire with a high CRI requires, in addition to the development of an optical system, power supply and cooling systems, to select LED light sources that would provide the required values of power and light efficiency. Today, ultra-high power LEDs are made in the form of COB modules, which are widely represented by global manufacturers of LED light sources. Their power can be 500 W and higher. However, such high-power LED modules today have usually a low color rendering index, which limits their use in rooms that involve the use of luminaires with high quality color rendering.

In [52, 53], for lighting systems it is proposed to use the standard size of LED COB modules 38×38 mm, for which models with a power of 200…525 W are available. More common and commercially available LEDs with CRI of more than 90 and light parameters close to natural are LEDs available in sizes from 18×18 to 30×30 mm. But these COB modules usually have a lower rated power of 50…104 W, so to create ultra-high power lighting systems (200 W and more) it is advisable to use not one but several LED COB modules. Another important advantage of LED COB modules with a maximum power close to 100 W is their low supply voltages (less than 40 V), which simplifies their power supply systems from renewable energy sources, such as solar panels.

Given that this work envisages creation of a lighting system capable of providing a high value of CRI at high light efficiency, a preliminary study of light and spectral parameters of industrially available and common LED COB modules manufactured by Cree Company size 23.85×23.85 mm CMA2550 (CMA2550-0000-00PN0U0A40G) [54].

Determination of light and spectral parameters was carried out using modern metrological equipment of the V. Lashkaryov Institute of Semiconductor Physics, NAS of Ukraine – matrix spectroradiometer Instrument system CAS-140 (Germany) and an integrating sphere with the diameter 2 m, which allowed controlling in real time the amount of radiated light power and determining the time of its stabilization. In general, the studies were performed according to the method described in [22].

The power supply unit HAMEG HMP4040 manufactured by Rohde & Schwarz Company (Germany) was used to supply power and determine the electrical parameters of the LEDs (current, voltage, power).

The use of a spectroradiometer also allowed determining the spectral distribution for the selected type of LEDs (Fig. 1). The normalized spectrum of the LED light source at the nominal current 1400 mA is shown in Fig. 1, curve *1*. As can be seen from Fig. 1, the spectrum of the LED COB module is typical for a LED light source, except for quasi-chromatic peaks at the wavelengths 608.5, 613.5, 631.0, 635.3 and 647.5 nm, which can be used to achieve a high luminous efficacy of radiation at high CRI [55].

To determine the effect of quasi-chromatic peaks in the wavelength range 600… 650 nm on the spectral parameters of the resulting light, the spectrum of LEDs CMA2550 was modified by a software method in accordance with the spectral distributions that characterize luminophors of this type (Fig. 1, curve *2*) [55].

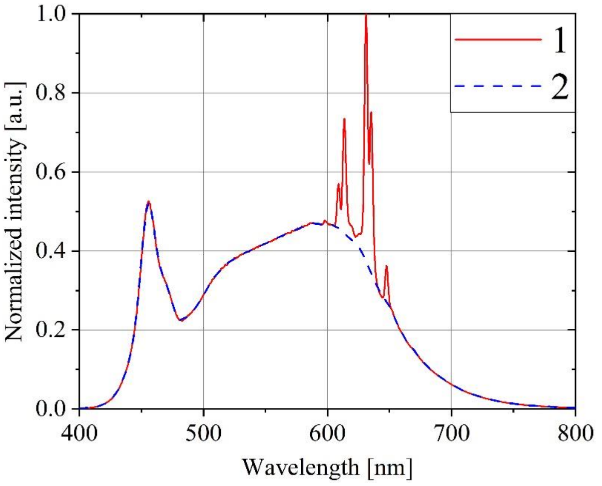


Fig. 1. Normalized spectrum of LEDs CMA2550 (1) and modified one within the wavelength range 600… 650 nm (2).

Table 1. Parameters of the spectra shown in Fig. 1.

Number of curve	L, lm	P_r,W	CCT, K	CRI	K, lm/W
1	6108	18.8	3888	93	325
2	5895	17.8	4293	85	331

The parameters of the modified spectrum were determined using the LED Color Calculator program [56], which allowed us to determine the following parameters: total luminous flux (L), correlated color temperature (CCT), CRI, radiated light power (P_r).

Additionally, the luminous efficacy of radiation (K) was calculated [25], in our case it can be determined as follows:

$$K = \frac{L}{P_r}. \qquad (1)$$

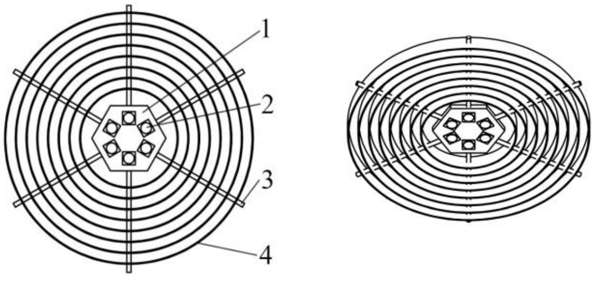
Table 1 shows a comparison of the parameters of the spectra shown in Fig. 1 and defined when using the LED Color Calculator program.

The data of photometric values listed in Table 1 indicate that when modifying the spectrum, the reduction of the total luminous flux was 3.5%, while the radiated power decreased by 5.3%, and the luminous efficacy of radiation increased by 1.8%. Modification of the spectrum increased its correlated color temperature from 3888 to 4293 K and decreased CRI from 93 to 85. It should be noted that such a change in color temperature (10.1% increase) is not critical and may even be invisible under certain conditions. At the same time, the reduction of CRI is important and one can talk about the use by the manufacturer of LEDs of approach that can significantly (by 7 units) increase CRI when maintaining high luminous efficacy of radiation.

2.2. Design features of the experimental sample of a powerful LED luminaire with high CRI

The design of a powerful LED luminaire, developed by the authors earlier, was chosen as the basic construction for the experimental sample [38]. To ensure the operation temperature modes of LED light sources, in this work an improved construction of the passive cooling system (Fig. 2) described in [52] was used. The improved passive cooling system consists of a body (*1*), on which 6 LED light sources (*2*) were fixed, 6 heat pipes (*3*) placed radially and 8 elements of heat exchange with air (*4*) that were made in the form of concentric rings.

The body of the lamp is made in the form of a base from aluminum alloy. Powerful LED COB modules are installed on one side of this base, and channels for installation of heat pipes are made in the base itself. The proposed construction of a compact cooling system with radial placement of heat pipes allows us to bring their heating zones as close as possible to powerful LED COB modules. Elements of heat exchange of the cooling system with air in this design are created in the form of concentric rings made of aluminum strip (Fig. 2).



a b

Fig. 2. Constructive scheme of the passive cooling system based on heat pipes with installed LED COB modules (in two different orientations): *1* – base of the cooling system; *2* – LED COB modules; *3* – heat pipes; *4* – heat exchange elements.

The construction of the passive cooling system provides free movement of air between the heat exchange elements to ensure efficient heat exchange with the air. By setting the power of LED light sources and ambient temperature using the optimization technique described in [53], the required number of heat pipes and cooling elements was determined, as well as their optimal geometric parameters were determined, too.

According to the optimization results, it was determined that when using 6 heat pipes with the length 250 mm and outer diameter 8 mm, it is optimal to use 8 heat exchange elements in the form of rings possessing the diameter of 180 to 480 mm with a step of 18 mm, they are made of the strip 30 mm high and 2 mm thick of aluminium alloy AD31.

Computer simulations were performed to determine the thermal characteristics of the optimized cooling system.

3. The results of modeling the thermal characteristics of the optimized passive cooling system for the LED luminaire

Computer simulation of the thermal characteristics of the cooling system was performed for LED light sources with a total heat output of up to 300 W. When using the optimal geometric parameters of the heat exchange elements, the minimum body temperature of the LED light sources was 91 °C. For lighting systems that must provide high reliability and long service life (*e.g.*, continuous lighting systems), it is important to ensure a low (up to 85 °C) temperature of light-emitting crystals to reduce the rate of degradation of LEDs and change in the luminophor characteristics. The temperature of the light-emitting crystals (t_j) is higher than the temperature of the LED body (t_c) and can be calculated by the dependence:

$$t_j = t_c + P_t R_{j-c}, \tag{2}$$

where P_t is the thermal power of LED, W; $R_{j\text{-}c}$– thermal resistance of 'crystal-case' of LED, in °C/W.

To perform calculations on the dependence (2), it should be taken into account that at the electric power of a light source (P_e) only its part that depends on its external quantum efficiency (η_e) is converted into light radiation. For modern industrially available LED light sources, η_e reaches usually 0.4…0.5, which corresponds to the conversion factor of the used electric power (P_e) into thermal energy (P_t) η_t = 0.6…0.5. To assess the possible power of luminaires, the calculated values of crystal temperature were obtained at certain values of thermal resistance between the crystal and the body of LED light sources and their efficiency presented in Table 2. The calculations assumed that the cooling system used 6 LED COB modules with $R_{j\text{-}c}$ = 0.1 °C/W and the coefficient η_t (part of the electric power used by LED, which was converted into the thermal energy) from 0.5 to 0.6, depending on the temperature of the light-emitting crystals.

It should be noted that during simulation the ideality of thermal contact between the base of the cooling system and the LED COB modules was accepted. The imperfection of the thermal contact between the COB modules and the base of cooling system increases the temperature of the LED body by a certain amount Δt as compared to the ideal thermal contact. To reduce the temperature difference in the contact zone, a heat-conducting paste is used. When using the heat-conducting paste, the temperature difference Δt in the contact zone can be calculated using the following expression:

Table 2. Calculated dependences of the temperature of light-emitting crystals t_j and the electric power P_e of the luminaire on the thermal power P_t dissipated by the cooling system.

P_t, W	t_c,°C	t_j,°C	P_e, W	
		at $R_{j\text{-}c}$= 0.1 °C/W	at η_t = 0.5	at η_t = 0.6
50	35.8	36.6	100.0	83.3
100	46.8	48.5	200.0	166.7
150	57.9	60.4	300.0	250.0
200	68.9	72.2	400.0	333.3
250	80.0	84.1	500.0	416.7
300	91.0	96.0	600.0	500.0

Table 3. Estimated dependences of exceeding the temperature of the body of COB modules t_c relatively to the mounting surface of the base for the studied range of thermal powers P_t.

P_t, W	t_c, °C	
	paste DeepCool Z3	paste KPT-8
50	0.9	1.4
100	1.8	2.9
150	2.7	4.3
200	3.6	5.8
250	4.5	7.2
300	5.4	8.7

$$\Delta t = \frac{P_t\, l}{\kappa S}, \tag{3}$$

where P_t is the thermal power emitted by LEDs of the COB module, W; l – thickness of the layer of deposited heat-conducting paste, m; S – contact area of the LED COB module with the base, m^2; $\varkappa$ – thermal conductivity of the heat-conducting paste, W/(m·°C).

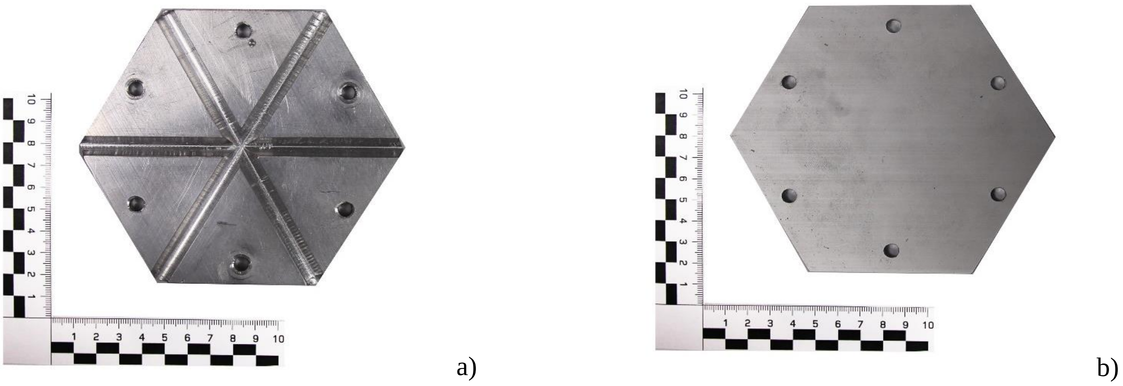
Table 3 shows the estimated values of the excess temperature of the LED COB module t_c relatively to the base of cooling system for the selected 6 LED COB modules of the size 23.85×23.85 mm using 2 different types of common heat-conducting pastes with an average thickness of the paste layer $7\cdot10^{-5}$ m.

Table 3 shows that the use of heat-conducting paste with higher thermal conductivity (DeepCool Z3) provides better thermal contact between the LED COB module and the base of cooling system, and, therefore, reduces the temperature of light-emitting crystals. An additional advantage of this type of heat-conducting paste is the lower viscosity, which simplifies its deposition by a thin layer and improves the filling of surface microroughness.

4. Production of an experimental sample for a powerful LED luminaire with high CRI

Using the performed calculations, an experimental sample representing the cooling system for a powerful ultrahigh-power luminaire capable of providing normal thermal modes of light-emitting crystals with a compact size of passive cooling system was fabricated.

The base of the experimental sample for this cooling system is made of aluminum sheet with the thickness 10 mm and has the shape of a regular hexagon with the side 66 mm. In this base, 6 radially located grooves were made by milling (Fig. 3a). In the radially



a) b)

Fig. 3. The base of the cooling system with the manufactured grooves (a) and the pressure plate (b).

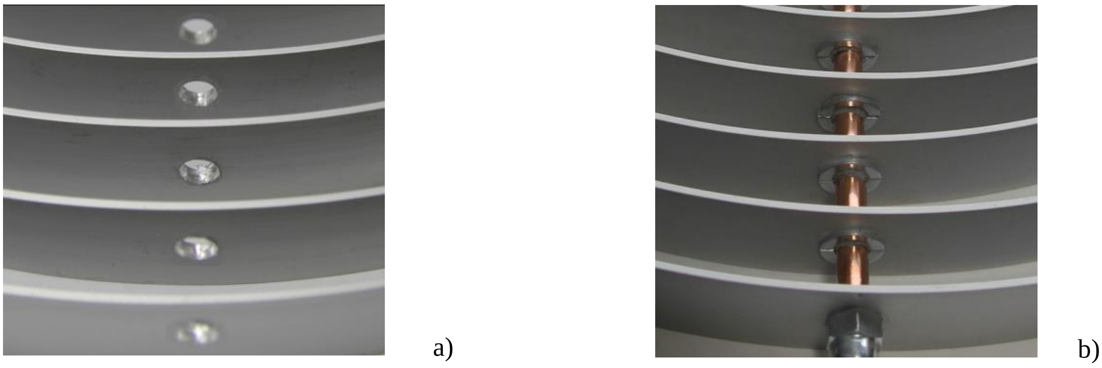

a) b)

Fig. 4. Heat exchange elements of the cooling system with manufactured holes (a) and with using heat-conducting glue and aluminum washers (b).

a) b)

Fig. 5. Photo of the cooling system with the installed LED COB modules (in two different orientations).

located grooves, zones of heating the heat pipes are fixed by means of an aluminum plate (Fig. 3b).Heat-conducting glue (Shenzhen Halnziye Electronic HY910-ST10G) is used to provide the thermal contact between the heat pipes and base of the cooling system.

Condensation zones of heat pipes were installed in the rings of the cooling system, in which the holes were made for this purpose (Fig. 4a), with additional use of heat-conducting glue and aluminum washers (Fig. 4b) to improve the thermal contact of the rings with heat pipes.

LED COB modules are fixed on the base of cooling system with using a layer of heat-conducting paste with a thickness of no more than $7\cdot10^{-5}$ m with the thermal conductivity 1.132 W/(m·°C) (DeepCool Z3) between the base of cooling system and the body of COB modules.

The general view of the made experimental sample of cooling system with the installed LED COB modules is shown in Fig. 5.

5. Investigation of thermal and electro-optical parameters inherent to the experimental sample of a powerful LED luminaire with high CRI

During the experimental studies, there were measured the temperatures of body of LED COB modules and electro-optical parameters of the luminaire from the moment of switching on to the moment of temperature stabilization, as well as reaching the stabilized values of power, light and spectral parameters.

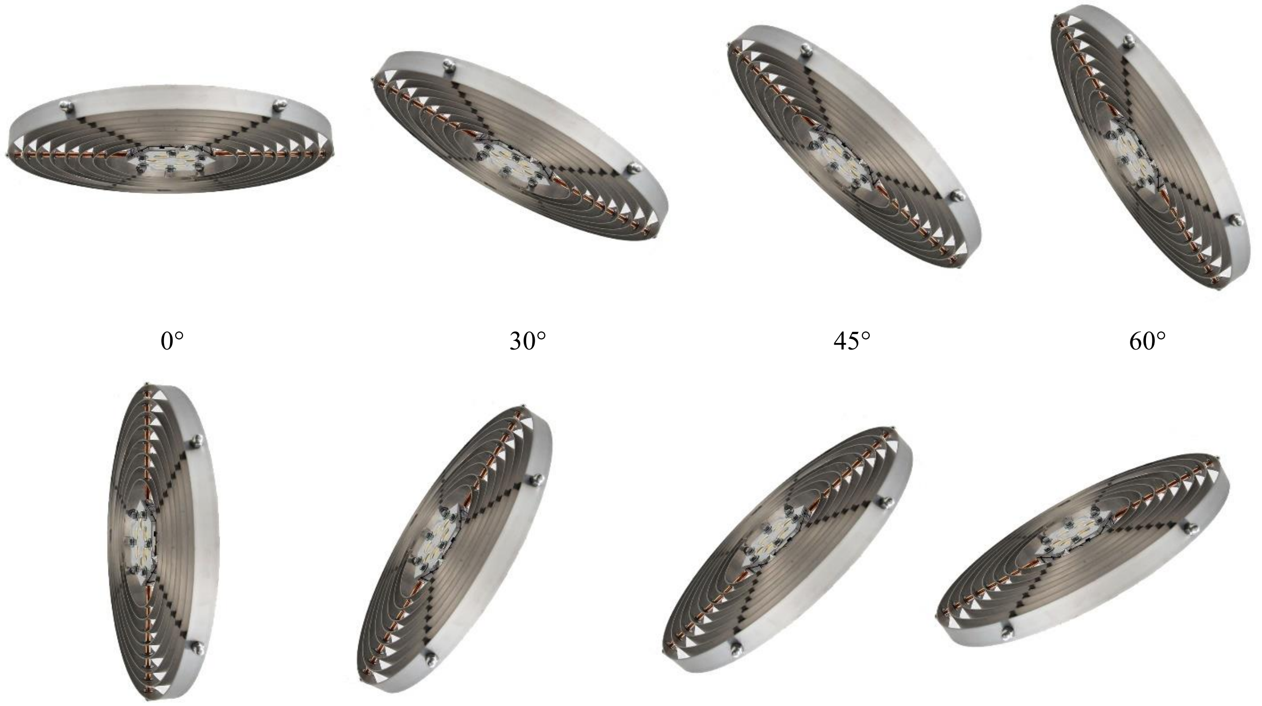
6 T-type thermocouples and a multi-channel measuring device YF-500 (Everfine Corporation, Binjiang National Hi-Tech Zone, Hangzhou, China) were used to measure temperature parameters. Thermocouples were installed on the body of each LED COB module. The performed studies have shown that the measured temperature values were different by up to 2 °C, so for the analysis of experimental data the temperature was used not for all, but one, the most heated, LED COB module.

All the experimental studies were performed inside the integrating sphere at a controlled ambient temperature of 20 ± 1 °C, and data recording took place after setting of a stationary mode of operation of the system in the selected mode.

Table 4 shows the measured values of the electro-optical parameters of the experimental sample of the LED luminaire (I – current, U – voltage, P – power, L – luminous flux, CCT – correlated color temperature, CRI – color rendering index, η_v – light efficiency) and body temperature of the most heated LED COB module (t_c), as well as the calculated temperature of the light emitting crystal (t_j).

Table 4. Electro-optical parameters of the LED light source.

I, A	U, V	P_e, W	L, lm	CCT, K	CRI	η_v, lm/W	t_c, °C	t_j, °C
1.000	31.783	32	4943	3851	92.4	156	21.9	22.2
2.000	32.727	65	9991	3860	92.4	153	25.6	26.2
3.000	33.390	100	14803	3864	92.4	148	36.9	37.8
4.000	33.974	136	19394	3868	92.5	143	46.7	48.0
5.000	34.469	172	23675	3875	92.5	137	55.8	57.5
6.000	35.062	210	27531	3880	92.5	131	63.4	65.5
7.000	35.655	250	31387	3885	92.6	126	71.0	73.6
8.000	36.247	290	35243	3889	92.6	122	78.6	81.7
9.000	36.840	332	39099	3894	92.6	118	86.2	89.8
10.000	37.433	374	42955	3899	92.7	115	93.8	97.9



0° 30° 45° 60°

90° –60° –45° –30°

Fig. 6. Photo of the placement of the luminaire in different spatial positions.

As can be seen from Table 4, the most appropriate is the use of this luminaire at a current of 8 A, which provides an electric power of 290 W, and the temperature of the light-emitting crystals is about 81.7 °C. These operation conditions allow us to say about the possibility of reliable operation of the lighting fixture for at least 100 thousand hours. During the research, it was determined that the created cooling system provides stabilization of the temperature of LED COB modules and their luminous flux for a time from 200 to 300 s at selected operation modes.

Given that heat pipes with a powder capillary structure function quite efficiently, and when the evaporation zone exceeds the condensation one, it was assumed that the luminaire can function effectively, even when it deviates from the horizontal position by a certain angle.

To determine the efficiency of the luminaire, a study of the experimental sample was performed when fixing it at different angles to the horizon in the range from minus 60 to plus 90 degrees, where 0 degrees – the main operation position, 90 degrees – the position, at which the luminaire is placed vertically, and negative angles correspond to the cases when the luminaire shines up (Fig. 6).

The dependence of the body temperature of the hottest LED COB module of the luminaire and its total luminous flux on the angle of inclination (α) to the horizon of the lighting system as a whole, and hence, the heat pipes, is shown in Table 5. To determine the angle of inclination to the horizon, an electronic level was used, the measurement error of which is 0.1°.

The use of developed ultra-high-power luminaires with high CRI is primarily effective for lighting a room with a large area and ceiling height. Usually, for lighting such rooms the luminaires of similar type are located horizontally, which provides high intensity of heat exchange with ambient air, however, as it is obvious from Table 4, the developed in this work luminaires with

Table 5. Luminous flux L of the luminaire, the body temperature t_c and the temperature of light-emitting crystal t_j of the most heated COB module at the current close to 8 A at different values of the angle of inclination α.

α, degree	–60	–45	–30	0	30	45	60	90
L, lm	35155	35210	35201	35243	35229	35215	35201	33920
t_c, °C	79.1	79.8	79.6	78.6	78.7	78.8	78.9	98.0
t_j, °C	83.2	81.9	82.7	81.7	81.8	81.9	82.0	101.5

passive cooling system based on heat pipes function quite effectively at location of the luminaire at an angle from –60° to + 60° to the horizon, which expands the scope of its application.

The ability to operate at a certain angle to the horizon and the high value of CRI allow one to use the selected type of luminaires as an element of lighting systems that provide their installation at an angle to the horizon (stage lighting, lighting the art objects, sport objects, *etc*.).

6. Conclusions

1. It is expedient to use LED luminaires with high CRI and efficient cooling the COB modules by heat pipes in continuous artificial lighting systems due to the possibility to combine the power supply of LED from the general power supply network and renewable energy sources, in particular the solar ones, for additional increasing the energy efficiency of these systems.

2. The spectrum of the selected type of LED light sources with high light efficiency and CRI has quasi-chromatic peaks within the range of 600…650 nm. It has been shown that the replacement of quasi-chromatic peaks of the spectrum in the wavelength range 600…650 nm with a typical spectral distribution for LED light sources of this type leads to a decrease in total luminous flux by 3.5%, radiated power by 5.3%, and an increase in the luminous efficacy of radiation by 1.8%. Spectrum modification increases its correlated color temperature from 3888 to 4293 K and decreased CRI from 93 to 85.

3. Developed and manufactured passive cooling system of LED COB modules based on heat pipes provides operation temperatures (up to 85 °C) of light-emitting crystals with the total electric power of 6 COB modules 290 W.

4. Studies of temperature and electro-optical parameters of the experimental sample of LED luminaire have shown that its cooling system provides stabilization of the temperature of LED COB modules and their luminous flux in no more than 300 s.

5. The possibility of functioning of the luminaire at different spatial orientations for electric power of 290 W has been shown. The results of the research have shown a slight (by 1…5%) increase in temperature of the light-emitting crystals, when the orientation of luminaire is changed relatively to the horizon within the range of angles from –60° up to +60°. The possibility of luminaire operation at some angle to the horizon expands the scope and allows one to use it as a directional light source.

6. The obtained research results can be used in the design of reliable high-power LED luminaires with a high value of CRI with uninterruptible power supply from a combined power supply for different applications.

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Надпотужні світлодіодні освітлювальні прилади з високим індексом кольоропередачі для систем освітлення з комбінованим електроживленням

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Анотація. У статті розглядається розроблення та створення надпотужних світлодіодних освітлювальних приладів з високою світловою ефективністю та індексом кольоропередачі (CRI). Як джерела світла використано 6 потужних світлодіодних COB (Chip-on-Board) модулів CreeCXA 2550, випромінювання яких містить квазіхроматичні піки в спектральній області 600…650 нм, що дозволяє забезпечити значення CRI, вищі ніж 92. Наведено особливості удосконаленої компактної конструкції освітлювального приладу із зазначеними COB модулями. Для забезпечення нормальних теплових режимів світлодіодних модулів створено систему охолодження невеликого розміру на основі теплових труб, оптимальні розміри конструктивних елементів якої визначено методом комп'ютерного моделювання. Результати моделювання та експериментальних досліджень показали, що розроблена та виготовлена пасивна система охолодження світлодіодних модулів забезпечує робочі температурні режими (до 85 °C) світловипромінюючих кристалів при сумарній електричній потужності модулів до 290 Вт і дозволяє використовувати освітлювальні прилади подібного типу в системах неперервного штучного освітлення з комбінованим електроживленням. Працездатність системи охолодження під кутами нахилу до горизонту розширює сфери застосування освітлювального приладу.

Ключові слова: енергоефективне освітлення, світлодіод, індекс кольоропередачі, повітряне охолодження, теплова труба.