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Light characteristics of high-power LED luminaire with a cooling system based on heat pipe

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Abstract. Discussed in the article is the possibility to create a wall-mounted LED luminaire with a built-in cooling system for a volumetric LED module put in the enclosed volume of the diffuser. The use of aluminum heat pipe with a threaded capillary structure has been proposed for cooling high-power LEDs of the volumetric module in the luminaire design. It has been shown that the use of heat pipe with a simple capillary structure allows the heat flux from the LED module to be efficiently transferred outside the light diffusing area to the decorative radiator located on the top of the lamp and to disperse it into the surrounding air. The proposed design of the wall lamp with heat pipe allows to increase the luminous flux and durability of the luminaire.

Keywords: LED, wall lamp, cooling of LED modules, heat pipe.

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1. Introduction

Approximately 19% of the electricity consumed in the world is spent on lighting [1, 2]. According to statistic [3, 4], in Ukraine, about 20…25% of the electricity is spent on lighting, in Russia 13…16%, in Belarus, 10…13%. At the same time, a significant part of this electricity (25…32%) is consumed by the residential sector [2, 3]. Until now, most of household lighting fixtures still use energy-consuming light sources – incandescent bulbs. Their disadvantage is the inefficient use of electrical energy, since most of the electrical energy goes to heat the surrounding air. The reason for the widespread use of incandescent pads is their low cost and availability for wide sections of the population. In this regard, the problem of saving electricity in household lamps, general and local lighting is relevant and needs to be solved.

At the same time, the tendency towards an increase in standards of living of the population and an increase in the number of middle-age and old aged population require consideration of the physiological characteristics of such people. In 1980, there were about 378 million people in the world who were 60+. According to a forecast, by 2050 there will be 2 billion of them. Due to human eye aging processes, the requirements for the necessary brightness of illumination increase for seniors. At the same time, all lighting standards are calculated for people aged 20. Considering the age-related changes, for 40-year-old residents for a comfortable perception the light levels should be 2 times higher, for 60-year-olds – 4 times, and for those over 80 years old – 30 times higher [5]. Modern recommendations for lighting require an increase in the level of illumination of both work areas and recreation areas, especially those with seniors.

One of the energy efficient ways to ensure the need for general and additional local lighting of residential premises is the use of LED pendant lamps (chandeliers) and wall lamps (wall lamps) based on LEDs. These luminaires are mainly intended for low power LED lamps with an E14 [6] base and, due to their features, do not always allow the use of high power lamps that are capable of providing the required luminous flux. The reason for this is very tight dependence of LED characteristics on the temperature [7]. Long-term operation at high temperatures and insufficiently efficient removal of the heat, which they release, leads to degradation of the semiconductor crystal of the LED, which adversely affects its lifetime, light characteristics and color parameters [8, 9].

Fig. 1. A sample of the "sconce" luminaire (a), which was selected for research with an 8 W LED lamp (b).

In addition, in modern high-power LEDs, due to the low thermal conductivity of the polymer binder elastomer, the heat that is released in the phosphor during energy conversion leads to local overheating, which significantly reduces the efficiency of LEDs, shifts the maximum of their emission spectrum, and significantly reduces the life time [10]. S.V. Smirnov *et al.* [11] showed that a decrease in the luminous flux of white LEDs based on gallium nitride and its solid solutions at elevated temperatures is associated with both a decrease in the external quantum efficiency of the crystal and a decrease in the efficiency of a phosphor coating based on yttrium-aluminum garnet doped with cerium. At the same time, there is also an increase in the correlated color temperature. The studies performed by Yu.A. Basova [12] showed that increasing the temperature of the most heated zone of the LED lamp radiator by 65…70 °C can increase its correlated color temperature by almost 1000 K.

The main source of the overheat of lamps of this type is the presence of a decorative light diffusers, which limits the access of cold air to light-emitting elements, during operation of which the thermal energy is released. Elevated temperatures inside the light diffusers lead to accelerated degradation and destruction of materials used in the luminaire, and manufacturers often place restrictions on the use of high-power incandescent lamps due to the danger of destruction of the luminaire design. At the same time, the power of the maximum allowable use of LED lamps in them is usually not specified.

The introduction of additional vents into the light diffusers [13] does not fundamentally solve the problem. To improve the efficiency of heat removal from LED light sources, it is promising to use of heat pipes and steam chambers [14–20], which have a thermal conductivity much higher than metals [21, 22], and which allow to remove high local heat fluxes from LEDs and output heat in a constructively convenient place to scatter it into the surrounding air. The exaggeration of a five-arm LED chandelier with a frame made of heat pipes [20] and mounted on them using a threaded connection [23] with bulk LED modules made it possible to double (up to 26.7 W) the power and luminous flux of each module. At the same time, the temperature of the housing of LED matrices did not exceed the value of 56 °C.

Given the small size of the wall-mounted luminaires, it is impossible to place LED lamps having a massive cooling system inside the luminaire, and often a closed or semi-closed light diffusers reduce the performance of the lamp cooling system due to the absence of intensive air exchange with the external environment. Thus, in wall lamps of a similar design it is permissible to use only low-power lamps, which is often insufficient to provide the required level of illumination.

In this work, the goal was to develop a heat removal system based on a heat pipe for a wall-mounted LED luminaire and create an LED lamp of the "sconce" type of the original design with improved photometric characteristics capable of ensuring that the LEDs work in the optimal temperature range.

2. Design of a luminaire with a cooling system based on heat pipe with a threaded capillary structure

The industrial sample of the wall lamp (Fig. 1a) of a common design was taken as a basis. To obtain results that allow evaluating the efficiency of the designed cooling system, comparative studies of the luminous characteristics of the luminaire were carried out by using an industrial LED lamp with a nominal power of 8 W (Fig. 1b) with installed LEDs and using a volumetric LED module in an upgraded luminaire with the heat pipe. Production LEDs used Cree, model MHBAWT-0000-000C0UA430H [24], for which the thermal resistance between the LED case and the *p-n* junction is 5.5 °C/W made it possible to accurately enough estimate the crystal temperature by measuring the temperature of the LED case. So, despite the fact that this type of LEDs allows a junction temperature of 150 °C, the documentation for them indicates that at this temperature there is a decrease in luminous flux after temperature stabilization by more than 20% of the nominal, which is quite a high indicator. Thus, while testing LEDs for a predictable lifetime [25-27], a decrease in the luminous flux of LEDs by more than 20% is considered by the manufacturer as an LED failure. In addition, the mode of operation of LEDs in extreme temperature conditions leads to accelerated degradation and a much shorter lifetime, as indicated by the relevant studies of manufacturers of LEDs [28].

In this work, LEDs were explored at maximum temperatures of the *p-n* junction, close to 100 °C, since at this temperature the decrease in luminous flux after temperature stabilization at maximum power is up to 10%. At the same time, the lifetime of these LEDs is not significantly reduced.

In order to improve the temperature conditions of operation of LEDs, in V. Lashkaryov Institute of Semiconductor Physics, National Academy of Sciences of Ukraine, together with NTUU "Igor Sikorsky KPI", a system was developed for heat removal of the original design based on a gravitational heat pipe (Fig. 2).

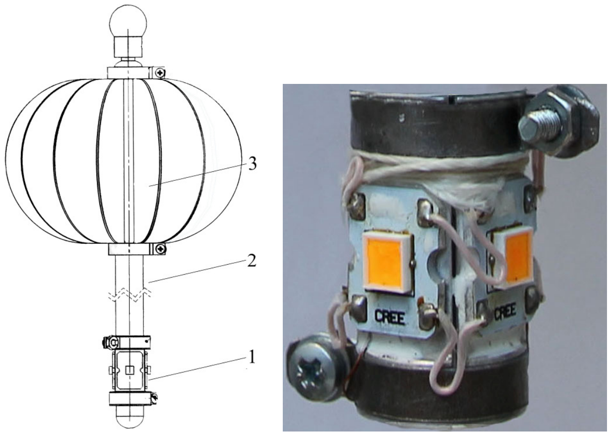

Fig. 2. Cooling system based on heat pipe (a) and volumetric LED module (b). *1* – volumetric LED module, *2* – heat pipe, *3* – decorative radiator.

Fig. 3. The appearance of the sample lamp with a cooling system based on heat pipe.

A developed volumetric LED module (Fig. 2b) consisting of 4 LEDs was used as a light-emitting element.

The scheme of the cooling system based on the gravitational heat pipe is shown in Fig. 2a. The LED module (Fig. 2b) is in the thermal contact with the heat pipe that transfers its thermal energy to the edges of the decorative cooling radiator.

This cooling system was integrated into the wall lamp (Fig. 3). The heat resistance of the heat pipe between the heating and cooling zone was 0.4 °C/W with the heat flow close to 15 W, which made it possible to significantly increase the heat transfer capacity of the cooling system and divert heat to the zone in which the placement of the decorative radiator would be most rational. The diameter of the heat pipe used in the construction is 12 mm and the length is 200 mm. When using a homogeneous material to achieve the same thermal resistance, a single bar diameter of 22 mm would be required, if it was made of aluminum and 16 mm of copper. At the same time, the mass of such rods, and hence the amount of material for their manufacture, would be 3 times higher than in the developed heat pipe.

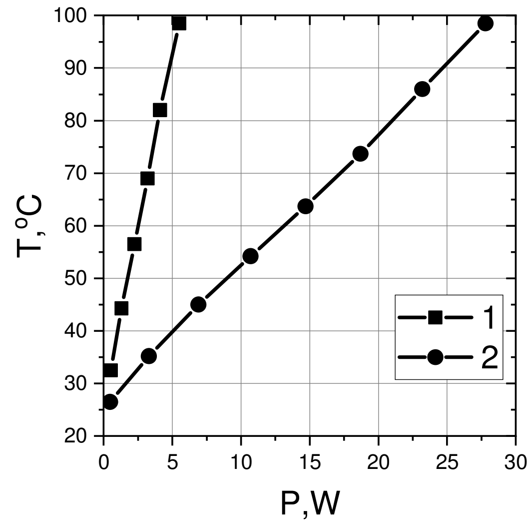

Fig. 4. The dependence of the temperature *T* of the *p-n* junction of LEDs on the power *P* of the LEDs when using a standard radiator from an E14 lamp (*1*) and a cooling system based on a heat pipe (*2*).

3. Experimental research of the characteristics of a wall lamp with a cooling system based on a heat pipe

The study of the photometric, electrical and thermal characteristics of an industrial wall mounted LED luminaire with an LED lamp and the LED lamp design developed on its basis with a volumetric LED module as well as a cooling system based on a gravitational heat pipe with a threaded capillary structure was carried out experimentally.

The studies were performed using metrological equipment of the Research Laboratory “Laboratory Center for testing and diagnostics of semiconductor light sources and lighting systems based on them”, ISP NAS of Ukraine. The equipment included an integrating photometric sphere with a diameter of 2.0 m and a high-precision CES-140 matrix spectroradiometer manufactured by the “Instrument System”, a HAMEG HMP4040 power supply, and a multi-channel YF-500 temperature meter.

The results of research are presented in Figs. 4 and 5. Fig. 4 shows the dependence of the temperature inherent to the *p-n* junction of LEDs on the power, when using a standard radiator based on a basement lamp (1) and an original cooling system based on a heat pipe with a decorative radiator (2). The ambient temperature was 25 °C.

Fig. 4 shows that with increasing power, the temperature of the LED crystals changes linearly, but in both cases the temperature value reaches the selected threshold of 100 °C at different power values. The graphical dependences show that as compared to using the traditional LED lamp radiator, the use of heat pipe

LED case temperature of the analyzed types of LED light sources.

Type of LED light source	The temperature of the body of LEDs, °C
LED Bulb E14 with industrial radiator	85
Volumetric LED module with cooling system based on the heat pipe and decorative radiator	60

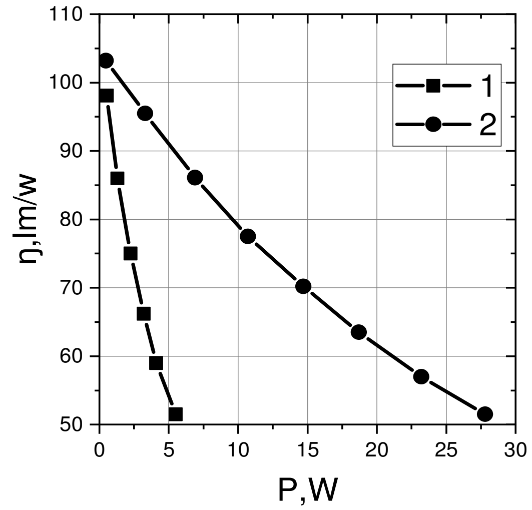

Fig. 5. The dependence of the luminous efficiency η on the power *P* when used as a heat sink device is the standard radiator from an E14 lamp (*1*) and a cooling system based on the heat pipe (*2*).

as a heat removal device made it possible to ensure the temperature of LED crystals to be at a previously selected level (100 °C) at a higher luminaire power (27.6 W instead of 5.4 W).

Recently, LED manufacturers have begun to give data on the predicted decrease in the level of luminous flux measuring not the temperature of the *p-n* junction, but the temperature of LED casing. Measured in this study, the temperatures of the housing of LEDs for both cases are shown in Table.

Our experimental studies showed that using the industrial E14 radiator, the maximum temperature of LED housing was 85 °C, which corresponds to the predicted operation time without reducing the luminous flux by more than 10% – 21 000 hours. Using a cooling system based on heat pipe and a decorative radiator, the maximum body temperature of the LEDs was 60 °C. In accord with the data provided by the manufacturer, the projected time of the LEDs without reducing the luminous flux by more than 10% in this case will be over 60 000 hours.

Thus, the introduction of the heat pipe into the luminaire design makes it possible to increase almost 3 times the predicted lifetime of the LED light source.

Fig. 5 shows the change in luminous efficiency of the luminaire using an E14 basement lamp with a standard radiator (1) and using a volumetric LED module with a cooling system based on the heat pipe and a decorative radiator (2).

As mentioned above, earlier in the course of experiments, the maximum power of LEDs was chosen so that the temperature of the crystals would not exceed 100 °C. At the given crystal temperature, in case of a lamp with a cooling system based on heat pipe, the power of the LED module is close to the maximum used for LEDs. To facilitate the mode of LEDs, we have proposed an improved module design. Increasing the number of LEDs improves the design of the LED module and will reduce the current through individual LEDs. In this case, the temperature of the *p-n* junction will be reduced and the luminous efficiency will be increased. The luminous flux remains at the same level.

Using the industrial E14 radiator, power limitation of the LED module is associated with a lower radiator’s ability to dissipate heat, which limits the luminous flux when LEDs operate in the selected temperature mode.

From Fig. 5, it can be seen that, with the output powers of these light source designs (5.4 and 27.6 W), we obtain the light efficiency of the finished lamp 51 lm/W. Therefore, the luminous flux of the original lamp, as compared with the industrial design of the lamp, increases from 281 to 1420 Lm, that is, 5.1 times.

According to the measurement results, the thermal resistance of the cooling systems was calculated. For a lamp with a base lamp E14, it was 13.6 °C/W, and for the original cooling system based on the heat pipe – 2.7 °C/W.

The low thermal resistance of the cooling system with the heat pipe allows to increase the power of the lamp from 5.4 to 27.6 W, which is 5.1 times higher, while it does not exceed the recommended power of LEDs used and keep the temperature of the crystals no higher than 100 °C. Then the light luminaire efficiency is above 51 lm/W. The heat pipe allows setting the mode in which from the moment of switching on till temperature stabilization of the LEDs, the decrease in the luminous flux is within 10% of the nominal.

It should be noted that when using direct-replacement LED lamps in the luminaire, in which the driver is installed, the power dissipated by them also contributes to raising the temperature of the LEDs. In addition, industrially manufactured LED lamps use light-emitting diodes with extreme temperatures of 85 °C, which lowers the maximum power of LEDs (of similar luminous efficiency) to 3.8 W. Using a driver with an efficiency of 92%, we reach a limit on the maximum power of the lamps used within 4.5 W without taking into account additional heating from the driver. In this case, the LEDs will operate in the modes of maximum allowed temperatures.

4. Conclusions

1. The results of the study of the light and thermal characteristics of the LED lamp for direct replacement of E14 in a wall lamp of the "sconce" type indicate that the operation of LEDs of industrial LED lamps with a power exceeding 4.5 W in the wall lamp occurs in more severe temperature conditions, significantly reducing their lifetime.

2. The use of a volumetric LED module with a cooling system based on heat pipe and a decorative radiator in the wall lamp design allows to create a cooling system that provides the *p-n* junction temperature of LEDs within 100 °C, even with an increase in the light source power by the factor of 5.1.

3. The proposed original design of the cooling system makes it possible to extend the estimated operation time of the LEDs without constantly reducing the luminous flux by more than 10%, 3 times as compared to an industrial lamp with a standard radiator.

4. Reduction of the light flux of LEDs in a volumetric LED module with a cooling system based on heat pipe during temperature stabilization occurs within 10%, while in an industrial E14 LED lamp with a standard radiator – more than 20%.

5. The use of an improved LED module in the proposed lamp design consisting of 6 LEDs operating at 50% of maximum power will increase light efficiency by 29% (up to 66 Lm/W). Although at the same time, the luminous flux of the luminaire will remain at the same level, the electric and thermal modes of LEDs will become more lightweight, and that will increase the life time of LEDs.

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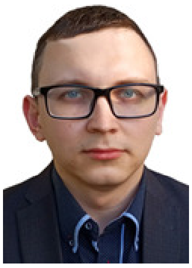

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