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HYBRID LIGHTING COMPLEX FOR COMBINED LIGHTING SYSTEMS: RESEARCH INTO OPTICAL PATH OPTIMIZATION USING THE COMPLEX "SOLAR LED-S" NEW MODIFICATION

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ABSTRACT

A new concept of the architecture of hybrid lighting systems for installations of combined lighting is considered. The cascade principle of constructing the optical path of such complexes is described, in which the design contains two stages of the cascade: the upper and lower stages. The upper (input) structure is made on the basis of the corresponding modification of the hollow tube "Solatube®" (daylight), and the lower one, based on the "Solatube®" fibre of a larger diameter, is combined with LED artificial light block and is designed to transmit mixed light (daylight and artificial light). The results of studies on the efficiency of light transmission made it possible to optimize the solution of the new modification of the hybrid lighting complex "Solar LED", lower stage of the cascade, and to develop the nomenclature of the production line "S". The description of the first experience of using this complex in the pilot combined illumination system of the "meeting room" in the shopping centre "IKEA Belaya Dacha" headquarters is given. A completely autonomous power supply system for a lighting installation based on solar panels has been implemented.

Keywords: system of combined lighting, hybrid lighting complex (HLC), daylight, artificial light, hollow tubular light guides (HTLG), optical cascade, LED artificial light block (LED-ALB)

1. INTRODUCTION

Despite the recent appearance of the first prototypes of hybrid lighting complexes (HLC), the evolutionary path of their development in the technical, economic and social aspects is now visible [1].The first domestic experience of using combined lighting systems (CLS) based on the "***Solar LED-S***" has confirmed the expected (calculated) parameters of the lighting system and effects: energy efficiency and high quality of the light environment. At the same time, during the installation and subsequent operation of the HLC, two significant drawbacks were identified, the elimination of which would significantly increase the consumer qualities of these devices [1]:

• Artificial light block (ALB), placing the LED in the collimator zone (similar to the construction described in [2]), causes a high percentage of reflected light ("reverse"), which manifests itself in a fairly bright glow of the domes at dark time, Fig.1, a. Calculations showed that the back luminous flux of the LED unit is about 22% of the total, which significantly reduces the energy efficiency and efficiency of HLC. The effect of the "reverse" reflection of the luminous flux of the LED modules (LED-M) is shown at Fig. 1, b (photo from the dome side on the roof). A radical solution of this problem is achievable with such an arrangement of the LED emitter in the cavity of a hollow tubular fibre (HTF), in which the optical axes of the LED-M

Fig.1. The illumination manifold as a result of "selling" reflections of the LED module luminous flux (a) and mirror reflection LED module (top view through a manifold in the channel of hollow tubular light guide) (b)

and the HTF and the plane of the reflecting surface of the HTF are parallel, which will significantly reduce the return luminous flux as a result of reflections from the inner surface of the HTF. The study of the optical pathway of HTF and of HLC in the context of the foregoing is described below.

• Placement of ALB inside the room with a large height of the diffusers installation creates serious operational problems with ALB and its automatic control system (ACS). In particular, the installation and maintenance of the mine at a high installation height (5–20) m necessitates the construction of additional structures for access to the HLC or the attraction of industrial climbers for work. This causes complication and increase in cost of installation, repair and maintenance of ALB, which contradicts the innovative spirit of HLC. Below are the technical solutions that reduce the severity of this issue.

Solving the named problems, the authors changed the concept of the architecture of the HLC and conducted studies of its optical path, aimed at increasing the efficiency of the transmission of the luminous flux of ALB through the optical channel of the HTLG. Based on the research, the new HLC named ***"Solar LED-S"***is proposed constructively and a series of modifications is presented.

2. A NEW CONCEPT OF THE OPTICAL PATH OF THE HLC

The design of the HLC***"Solar LED-S"*** implements a cascade principle of constructing an optical path [3, 4] represented by two stages: the upper and the lower. The upper (input) stage of the cascade is combined with a light-receiving dome and is made on the basis of a corresponding modification of the "Solatube®" (daylight), and the lower stage of the cascade is based on the "Solatube®" of larger diameter, following in a series of modifications "Solatube®" – combined with LED-ALB and is designed

Fig.2. Decomposition of HLC "Solar LED-S" (based on HTLG Solatube® M74"):
1– collector "Solatube® M74 "series " SkyVault";
2– external dome;
3 –internal protective dome; 4–element of protection against liquid penetration; 5 – border fleshing; 6 – ring, fixing the light guide;
7–light guide of the upper stage of the optical cascade;
8 –annular mounting plate where LED units, radiator cooling and control unit (CU) of LED modules are hermetically mounted(each LED module is fixed on the end surface of the cooling radiator so that after installing the radiator on the mounting panel LED module is turned into the cavity of the lower stage of the optical cascade);
9–light guide of the lower stage of the optical cascade;
10–ring fixing the lens; 11–prismatic diffuser

Fig. 3. Appearance of the units of the product line of HLC "Solar LED-S" of the corresponding modification

to transmit mixed light (daylight and artificial). Detailed description of modifications of the HTLG "Solatube®" is given in article [5].

In the HLC ***"Solar LED-S"*** (Fig. 2), unlike its predecessor – HLC "Solar-LED", LED-M are located on the mounting panel in such way that the front side of the printed circuit Board LED-M faces into the cavity of the lower optical stage. In this combination, the optical axes of LED-M, HTLG and plane of the reflecting surface of the HTLG are parallel, thereby eliminating the most likely causes of "reverse light" in the HLC.

3. RESEARCH OF THE HLC LOWER OPTICAL STAGE

First, we note that the upper stage of the optical path has the configuration and parameters of the HTLG, in design of which has not been made any changes. A feature of the lower stage of the optical stage of the HLC is the integration of natural and artificial (LED) light transmission systems. The lower stage conveys mixed light. The mounting plate with built-in LED blocks (Fig.2, item 8) combines the stages of the cascade and acts as a transition node from the upper to the lower stage [4].The lower stage of the optical cascade along the entire length is a hollow tube of the same diameter. This decision of the HLC was preceded by studies of the optical path of the lower stage of the cascade by computer simulation in the software environment of "Light Tools". The efficiency η_i of the luminous flux transmission by the optical path HLC is the desired result and a criterion for comparative evaluation of design solutions. The following initial conditions are accepted for modelling:

- The angle of divergence of the light beam LED-M α is equal to120°;
- Length of the lower stage of the optical path L is equal to 600 mm;
- Input luminous flux (input of LED-M) Φ_{in} is equal to 12000 lm;
- The HTLG inner surface reflection coefficient is equal to 99,7 %;
- Φ_{out} is the luminous flux measured at the plane of the HLC diffuser;
- η_i is the ratio $(\Phi_{out}/\Phi_{in})\cdot 100$ %.

The results of computer modelling and calculations are given in Table. 1.

The results of modelling and evaluation of the η_i depending on the design solution, confirm the correctness of the selected configuration of the lower stage of the optical stage, at which the $\eta_i > 99$ %. The obtained simulation data were used as the basis for the development of optimal design of HLC ***"Solar LED-S"***.

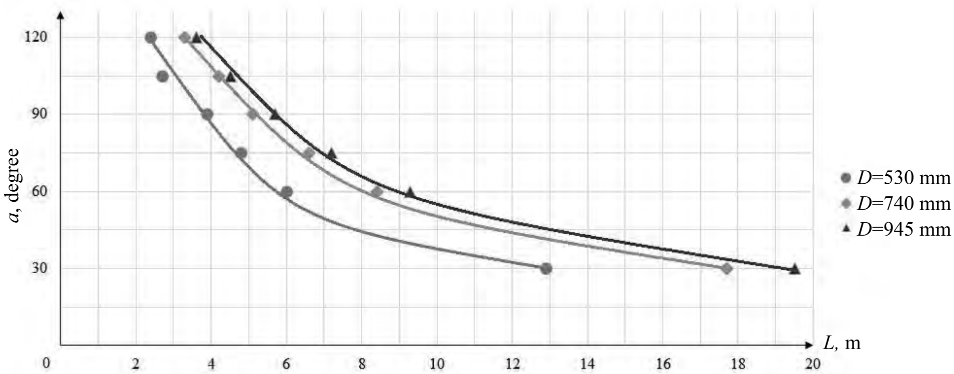
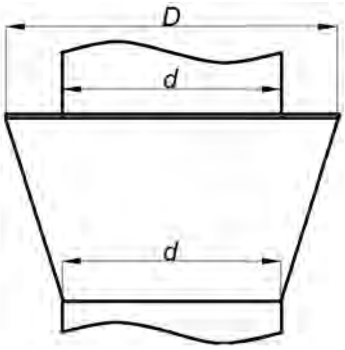
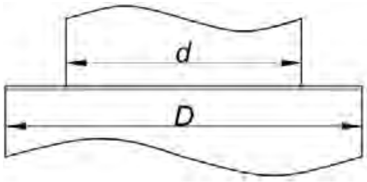
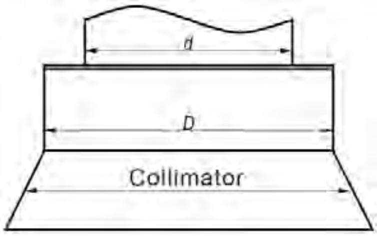
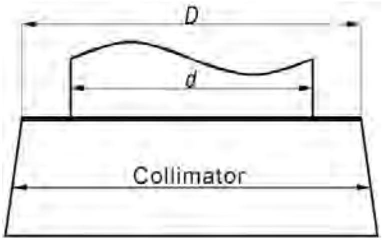


Fig. 4. The dependence of the maximum length L of the lower stage of the optical tube cascade HLC (in which the light transmission efficiency $\eta_i \geq 95$ %) from the divergence of angle α of the light beam of LED module

Table 1. Efficiency η_i of Luminous Flux Transmission Depending on the Design of the Optical Path HLC

№ option's	A constructive solution of the lower level	Schematic image	η_i,%	*d*, mm	*D*, mm
1	Panel–truncated cone		53,7	350	530
2	Panel–pipe		99,3	350	530
3			99,5	530	740
4			99,6	740	945
5	Panel – the pipe with the transition to the collimator		99,6	530	740
6	Panel –collimator		99,8	530	740

4. NOMENCLATURE OF THE PRODUCTION LINE OF HLC *"SOLAR LED-S"*

The results of modelling and calculations, and the existing type of **HLC** "Solatube®" formed the basis for the development of the product line nomenclature of **HLC "*Solar LED-S*"** (Table. 2).

The table shows the nominal values of the daylight luminous flux $\Phi_{v,\,DL}$ for the corresponding modifications of the HLC "Solatube®" [1], which are the basic for determining values of the artificial luminous flux $\Phi_{v,\,AL}$. The latter are given taking into account the MF operating factor according to the instructions [6, Table 4.3]. For example, for rooms with normal environmental conditions, MF is assumed to be 0.71.

In accordance with the Table 2, Fig.3 shows the appearance for the HLC from the HTLG nomenclature **"*Solar LED-S*"** structures.

5. INFLUENCE OF LED MODULES SECONDARY OPTICS ON THE EFFICIENCY OF LUMINOUS FLUX TRANSMISSION IN AN EXTENDED HOLLOW LIGHT GUIDE (EHLG)

The variety of architectural and engineering structures causes the use of the different length HLC at the lower stage of the optical cascade, up to 20 m.

Table 2. Nomenclature and Characteristics of Modifications of HLC "Solar LED-S"

№ mod.	*Legend of modification HLC	**$\Phi_{V,\,DL}$, lm natural light	***$\Phi_{V,\,AL}$, lm artificial light	Complete set LED-ALB	Recommended installation height of the diffuser, m
I	350/ LED-ALB /530	3000	6000	4 LED-module × 15W 4 УУ	≤ 4
II	530/ LED-ALB/740	8000	12000	8 LED-module × 15W 8 УУ	≤ 7
III	530/ LED-ALB/740У	8000	12000	8 LED-module × 15W 8 УУ	≤ 7
IV	740/ LED-ALB/950	18500	27000	9 LED-module × 30W 9 УУ	> 7
V	К/740/ LED-ALB/950	30000	42000	14 LED-module × 30W 14 УУ	> 7

Comments.
The structure of the conventional notation is based on the principle of listing the top-down elements of the HLC. For example: modification III-530 / LED ALB /740C: 530-diameter of the tube of the optical fibre of the upper optical stage, mm; LED ALB-mounting panel with blocks of LED- modules; 740-diameter of the tube of the optical fibre of the lower stage of the optical stage, m; C-cone-shaped amplifier (collimator);** $\Phi_{V,\,DL}$ is the nominal natural light flow passed through the tube-light guide of the upper stage of the optical cascade; ***$\Phi_{V,\,AL}$ is the nominal luminous flux of LED-ALB passed through the tube-light guide of lower stage of the optical cascade.

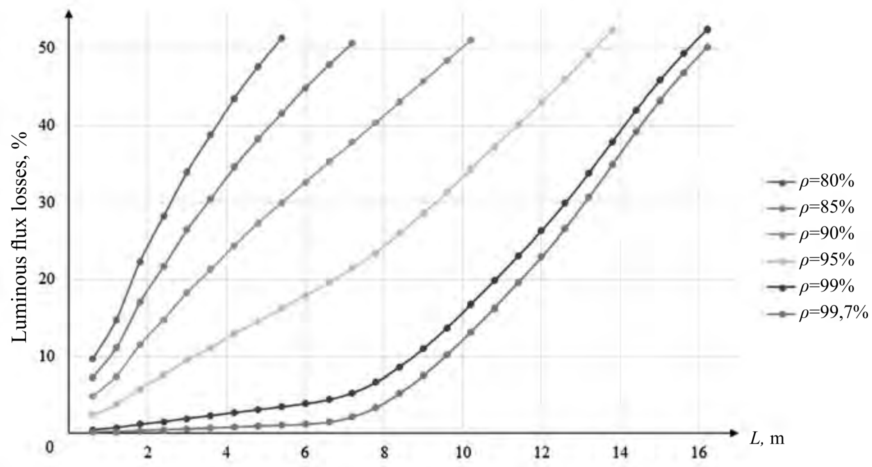


Fig. 5. Dependence of luminous flux losses on the length L of the light transmission channel having different reflection coefficients of the internal coating

In this regard, despite the high value of the reflection coefficients (99.7 %) of the light guide inner surface, light losses are possible due to the nature of light propagation along a hollow tube, determined by the angle of divergence of the light beam emitted by the LED module. Light loss limits the maximum light transmission distance according to the length of tubular guide. To assess optical losses and determine the distance of effective transmission of the luminous flux of the LED module by EHLG, authors studied the dependence of light losses on α within the process of optimization of the LED mo-

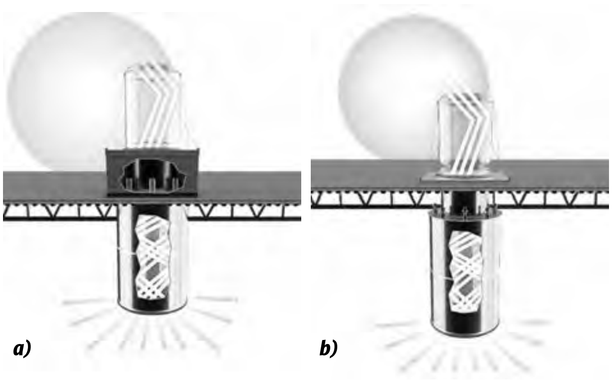


Fig. 6. Mounting options HLC “ Solar LED-S”:
a – outdoor installation, ALB set in the border; on roof;
b – interior installation, ALB is installed in the room

dule secondary optics parameters to evaluate the optical losses and to determine the distance of effective transmission of the LED-module luminous flux by EHLG. The research was carried out in the program “Light Tools” for the lower stages of the optical cascade as the lower stages have different pipe diameters. The loss of luminous flux at the level of 5 % corresponding to the distance of effective light transmission at the level of $\eta_i \geq 95$ % was selected as the boundary criterion for the selection of simulation data. The results of the study are shown in Fig. 4 and indicate the dependence of light losses on the divergence angle of the light beam of LED-M, which reflects the relationship of losses with the nature of multiple reflections and suggests the choice of optimal secondary optics for LED-M. Fig.4 shows that the best parameters are provided at $\alpha < 60°$.This determined the choice of secondary optics for optical system of HLC”*Solar LED-S*” with α in range (30–60) °. At the same time, such HLC provide high light transmission efficiency for most of the lighting projects of architectural structures. On the other hand, the optimal choice of the secondary optics for the lower stages of the optical cascade of different length allows minimizing indicators of the HLC price and provides the ability to control the light distribution in the plane of the diffuser, affecting the luminous intensity distribution curve (LIDC) of HLC light flow. The criticality of the choice of the material for the reflecting coating of the tubular hollow light guides demonstrates the dependence of light losses on the length of the light path at different reflection coefficients of the coating (Fig. 5).The dependence has a classical form, demonstrating the dynamics of growth of light losses when light propagates through the long hollow tubular light guides (as a result of multiple reflections) at a given coefficient of reflection of the coating. The coatings with a reflectance of 99.0 % and above have satisfactory performances for a long tubular hollow light guides (THLG).

6. PECULIAR PROPERTIES OF INSTALLATION OF HLC “*SOLAR LED-S*”

The new concept of cascade construction of the optical path of the HLC [3, 4] successfully solves the issue of exploitation, eliminating the hardship associated with a large installation height of the HLC. The solution of the problem lies in the location of ALB and control elements outside, above the roof of the building (exterior, (Fig. 6a). At the same time ALB is placed inside the border mounted on the roof. All the elements located inside the border are protected from the top by the border flash, which provides reliable water proofing. In each of the four walls of the border, there are service hatches, which provide access to the installation panel of the ALB for repair and maintenance work. Completeness of products of the nomenclature of HLC

Fig.7. HLC “Solar LED-S” in the “Meeting room “ (installation process). ALB is located in the space of the technical floor, located above the ceiling of the “Meeting room” under the roof (internal design)

Fig.8. Meeting Room (Daylight illuminance about 400 lx at high clouds of the sky. In sunny weather, natural light flow is regulated by means of dimmer, which allow to regulate the natural light flow and to perform a complete shutdown of natural lighting during video presentations)

Fig.9. View on the roof: HLC- inlet and solar panels

"*Solar LED-S*" is given in Table.2. Controlled ALB has a block structure that provides service without the use of special tools. The HLC design is made in such a way that between the upper stage of the cascade HTLG pipe, the border, the flushing and the panel, there is a free volume sufficient to accommodate the ALB and to perform works on their maintenance. At the same time, the service staff works on the surface of the roof of the building at the level of service hatches. In working condition, the hatches are closed with sealed doors. External construction and installation design minimizes the cost of installation, service and repair work in the maintenance of the HLC.

Cascade construction of the HLC has universality in terms of method and place of installation. In addition to the external design, there are options and internal installation, which may be preferable (Fig.6, b), as in the example of the application of HLC "*Solar LED-S*", given below (under certain circumstances or architectural features of the structure).

7. THE USE OF HLC "*SOLAR LED-S*"

In 2017–2018 years HLC "*Solar LED-S*", was first used in the "meeting room" of the shopping centre "IKEA Belaya Dacha" (Fig.7–9), with two modifications II – 530/ALB/740 – Table. 2, equipped with ACS and constant light sensor (Fig. 8) mounted on the ceiling between the diffusers. At the same time, a fully autonomous power supply system of the lighting system is implemented by means of solar batteries (Fig. 9).

8. CONCLUSION

Developed nomenclature of HLC "*Solar LED-S*" is innovative, designed to create high performance and, due to its universality, is applicable in almost any architectural solutions. The first experience of the HLC "*Solar LED-S*" in the "meeting Room" of the shopping centre "IKEA Belaya Dacha" initiated their implementation in the practice of lighting.

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