Hybrid Lighting System Research in the Context of Increasing Efficiency

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Abstract. A comparative analysis of the lighting and heat engineering parameters of typical light opening and combined lighting hybrid systems based on hollow light guides was performed. Hybrid lighting systems advantages over the typical light opening are the following: the ratio of the areas of light opening for a given illumination is 1/52; the ratio of heat inflows is 1/158; the ratio of heat losses is 1/170. The payback period of investments in hybrid lighting systems compared with the construction of typical light opening one, for example the shopping center, is less than 3 years. Taking into account the savings on the purchase of climate technologies, the payback is achieved at the design stage. Investigation results of the optical scheme of a hybrid lighting system and technical solutions are reported in the article. These results are aimed to optimize design and to increase efficiency of light transmission over an extended hollow light guides. The LED-block optics selection of the hybrid lighting system, which ensures the transmission of the light flux over distances of more than 20m is substantiated. The best parameters are achieved with the light beam divergence angle of the LED module in the range of 30-60 degrees, which determines the LED module secondary optics of the production product line of the hybrid lighting complex Solar LED-S.

1. Introduction

Trends in the construction of large areas with limited natural lighting, the development of underground space for the rational use of urban areas and optimization of infrastructure, the development of the program "energy-efficient building" and energy savings in lighting pose urgent problems of creating effective lighting systems and engineering solutions for the formation of a comfortable and safe light environment. "Energy-efficient building" concept involves comprehensive solution to the energy efficiency problems in optimizing energy balance of buildings. In such buildings energy saving technologies are playing a key role because they provides high quality buildings microclimate [1]. In this regard, the use of environmentally friendly renewable energy sources is uncontested. The strong emphasis on natural light is welcomed. The development of effective natural light input systems determining the roofs design, ceilings and roofing of buildings is gaining relevance. Typical systems are used in construction: vertical windows and rooflights. Together with the lighting facility (LF), the light openings form a combined lighting system (CLS), functioning in a natural rhythm of light time,
the performance characteristics of which depend on the parameters and quality of the light apertures, efficiency and rational use of the LF.

2. Combined lighting systems today

The active introduction of hollow light guides (HLG) into natural light systems and LEDs into artificial lighting has marked a new stage in the improvement of the CLS. Integration light guides in technique and in natural lighting technology is due to the progress in the record material reflectance value creation (99.7%) over the entire visible light spectrum. Such technological breakthrough in the field of reflective material provide creation of background light transmission systems for long distances with low loss and the spectrum high quality. Hollow light guides advantages in front of typical light openings in the part of thermophysical technologies allow to create a comfortable microclimate in the room with minimal energy costs [2].

HLG of the world's leading manufacturers are brought to a high degree of perfection. Also they are optimized for natural light transmission [3-6], which was the basis for the development of hybrid lighting systems (HLS) based on the HLG. In fact, this process is a natural and progressive stage in the evolution of CLS, when structural and radiating components are integrated into a single structure (Fig. 1): HLG, next-generation LEDs and automatic control system (ACS) [7-10]. The use of a new generation of LEDs with a spectral characteristic close to sunlight [11,12] in HLS provides a comfortable light environment in combined and artificial light modes. Smooth change of the artificial component by the ACS, depending on the level of natural illumination, makes the transitions in the dynamic system natural - mixed - artificial light invisible to the eye.

The structural unit of HLS, which unites all components of the system into a complete lighting product with characteristic properties and parameters, is a hybrid lighting facilities (HLF). Russian products HLF are represented by the Solar LED-S model (Fig. 1). HLF is positioned as an alternative to standard light openings, exceeding them by lighting and heat engineering parameters.

3. Comparative characteristic of light openings
Comparative analysis of CLS on the basis of HLF and typical light openings of the upper natural lighting, for example, the shopping center, has shown the best lighting and heat engineering characteristics of the HLF (Table 1) [2].

| Characteristic          | Ratio      |
|-------------------------|------------|
| The ratio of the areas  | 1/52       |
| Ratio of heat inflows   | 1/158      |
| Ratio of heat losses    | 1/170      |
| Ratio of $E_{min}/E_{max}$ | 0.6/0.1   |

| Comfort of light environment: |
|------------------------------|
| - typical light opening - high unevenness of the distribution of illumination, uncomfortable blinding brightness of direct sunlight, the presence of a sunspot wandering throughout the day; |
| - HLF - eliminate the shortcomings of typical light openings and create a comfortable light environment. |

Application of ACS in HLF increases the energy-saving effect by several times.
The discounted payback period of investments in HLF in comparison with the construction of standard light openings for a shopping center is less than 3 years. Taking into account the savings on the purchase of climate technology, the payback is achieved at the design stage.

HLF has emergency lighting functions in natural light mode and keeps these functions in artificial light mode with autonomous power supply from solar panels.

4. The optical path concept of the HLF

Energy efficiency and prospects for the HLF use stimulated research of the optical characteristics in order to increase the efficiency of light transmission through the optical channel of the HLF and the to develop the concept of optimal optical device scheme.

In optical systems consisting of inhomogeneous structure of optical transmission channels and light inputs light is spread as a result of multiple mirror reflections. In such systems light losses are inevitable due to light backward reflection. This effect was clearly manifested in the implementation of the project HLF Solar-LED application [14]. Light losses were estimated at 22% of the LED blocks light flux.

The solution to this problem determined the concept of the optical path in the new HLF Solar-LED-S model. The main idea of the concept is to create an optical scheme in which the plane of the mounting panel is oriented perpendicularly to the axis of the tube cavity. LED clusters located on the mounting panel and facing the radiating side inside the cavity of the lower level of the optical cascade. Therefore, the optical axes of the radiators, the cavities of the light guide and the reflecting cylindrical plane are parallel (Fig. 2). In such scheme, the causes of backward reflection over the entire length of the optical light transmission channel are eliminated.

According to the concept, the optical path is constructed on the base of cascade scheme [13,14], which contains the upper input and lower levels (Fig. 2). The upper input level is combined with the light receiving dome and is designed on the basis of the HLG Solatube® corresponding modification. The lower level on the base of a larger diameter HLS, next to the Solatube® series, is combined with an LED artificial light block and is designed to transmit mixed light.

In order to optimize the structural components of the HLF and achieve the maximum efficiency of light transmission through the optical channel, the system was investigated by computer simulation in the LightTools software environment.

5. Research of the HLG optical path

The upper level of the optical cascade has the HLG configuration and parameters. The lower level transmits mixed light. The mounting panel with integrated LED blocks (Fig. 1, position 8) combines
levels. Moreover, this panel is the transition point between the upper and lower levels of the optical cascade. The lower level is a hollow tube of the same diameter [15, 16].

The criteria for comparative evaluation of design options is the transmission efficiency of the light flux by the lighting system. Initial conditions for modeling are following: divergence angle of the LED modules light beam \( \alpha = 120^\circ \); length of the lower level \( L = 600\text{mm} \); input luminous flux is 12000 lm; the internal surface reflection coefficient of the light guides is 99.7%; registration of the output light flux at the diffuser plane of the HLF. The transmission efficiency of the light flux was estimated as the ratio of the output light flux to the input.

The results of computer simulation and calculations are shown in Figure 2 and Table 2.

![Figure 2](image.jpg)

**Figure 2.** The efficiency dependence of light flux transmission from the constructive solution of the HLF optical path.

| Optical path construction | Panel-truncated cone "funnel" | Panel-tube | Panel-tube-collimator | Panel-collimator |
|---------------------------|-------------------------------|------------|-----------------------|------------------|
| \( D, \text{ mm} \)       | 530                           | 530        | 945                   | 740              |
| \( d, \text{ mm} \)       | 350                           | 350        | 530                   | 530              |
| Variant number            | 1                             | 2          | 3                     | 5                |

### Table 2. Explanations to figure 2.

6. Investigation of the secondary optics effect of LED diode modules on the transmission efficiency of light flux in the light guides

Light losses limit the maximum distance of light transmission through the light guides. In order to determine the effective light transmission distance and to optimize the secondary optics parameters of the LED module, researches of the loss from the beam divergence angle are made.

Researches were provided for the lower levels of optical cascades, which are different in the diameter of the light guides. The boundary criteria takes the loss of the light flux at the level of 5% corresponding to the value of the transfer efficiency \( \eta \geq 95\% \) (Fig. 3). The dependence of losses on the angle of the light beam divergence of the LED module assumes the optimal secondary optics choice.
for the emitters. The best parameters were obtained for a divergence angle of less than $60^\circ$. This determined the secondary optics choice of the LED module for the HLF Solar LED-S with divergence angles in the range of 30-60$^\circ$. With such radiator parameters, high light transmission efficiency is provided for most CLS projects. Optimal secondary optics selection allows to optimize the prices of HLF and to control the distribution of brightness in the plane of the scattered, which affects the hybrid facilities light intensity distribution curve.

The criticality of the light guides reflective coating choice demonstrates the dependence of the light losses on the length of the light transmission path for various values of the reflection coefficient (Fig. 4). For light guides, satisfactory indices have coatings with a reflection coefficient more than 99.0%.

![Figure 3](image3.png)

**Figure 3.** The maximum length dependence of the lower level of HLF on the divergence angle of the light beam LED module.

![Figure 4](image4.png)

**Figure 4.** Dependence of light losses on the length of the light transmission channel from the HLG for different values of the coating reflection coefficient.
7. Conclusion
The results of comparative analysis of lighting and heat engineering parameters of typical light openings and combined lighting systems based on hollow light guides demonstrate the advantages of HLS. Based on the research of the HLS optical scheme, the cascade scheme for the optical path of the HLF of high optical efficiency design was proposed. The secondary optics selection of the hybrid lighting system LED block, which ensures the transmission of the light flux over distances of more than 20 m, is substantiated. The best parameters are achieved at the angle of the LED module light beam divergence in the range of 30-60°, which determined the secondary optics choice of the LED module for the HLF Solar LED-S.

A distinctive feature of the CLS is the stability of the light environment characteristics with a constantly changing quantitative ratio of its components. The automatic control system sets the programmable dynamics of the quantitative relationships between the components of the HLF with the constant of the illumination integral level.

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