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A HYBRID ILLUMINATION COMPLEX FOR COMBINED ILLUMINATION SYSTEMS: CONCEPTS, STATE OF THE PROBLEM, PRACTICAL EXPERIENCE

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ABSTRACT

Hybrid illumination complexes for systems of combined illumination are considered, including the concept of their development as a structural element of high energy efficiency and high quality light environment. The first practical application experience is described, of the project installed in a building of the MEGA Adygea Family Shopping Centre.

Keywords: combined illumination system, automatic control system, hybrid illumination complex, natural light, artificial light, hollow tubular light guide, artificial light LED unit

INTRODUCTION

In 2015–2016, a pilot project of the combined illumination system (CIS) based on the hybrid illumination complex (HIC) was installed in the MEGA Adygea Family Shopping Centre [1] (FSC) building. The entrance complex of the FSC "ASHAN" store served as the object of the illumination system reconstruction. Commissioning an illumination system reconstruction using innovative illumination technology naturally raises caution exacerbated by the relatively high capital costs of CIS construction. Without doubt, convincing and objective information about the prospects of CIS on the basis of HIC, their technical advantages and favourable economic indicators, in particular, their attractive payback period for innovative lighting systems, should play a decisive role in dispelling doubts and influencing the right decision.

HIC Concept for CISs

A significant increase in the economic, environmental and social efficiency of lighting, together with increased safety and comfort, can be achieved through the use of new and improved innovative technologies. HICs are especially attractive because they realise the potential of costless natural light. Engineering and technological approaches to realising natural light potential include advanced facilities of light transmission using hollow tubular light guides (HTLG)[1, 2]. Their use in buildings becomes a source of creative inspiration for architects and designers. Using a combination of natural light resources with energy efficient artificial light powered by automatic control systems (ACS), together forms CISs. Their distinctive criterion is stability of light environment characteristics due to compensation of the natural component changing in time by a correspondent correction using the artificial component (electric illumination). CISs based on HIC offer a holistic solution for modern architectural approaches to high energy efficiency illumination systems. The advantages of HICs in comparison with traditional solutions offer the challenge of their ap-

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plication: a compactness of architectural and design structural solutions; a comfortable light environment; high energy efficiency; a dynamic control parameter of a room's light environment.

The flexibility and high energy efficiency of CISs have inspired very original engineering solutions [3–7]. A natural result of the evolution of a computer-controlled CIS is that the three interconnected components: an HTLG (natural light), an LED light source (artificial light) and an ACS [8–11], determine the characteristics of the system only when acting in unison. Such a system is correspondent to the HIC term and according to GOST [12], the following definition is applicable: HIC is a device intended for a combined illumination uniting two light source types (natural and artificial) integrated into one whole structure together with an automatic control system and with general technological documentation ensuring a combined illumination and performing its functions to the consumer in the assembled condition.

HICs combine a hollow tubular light guide (HTLG) and an artificial light unit (ALU) with radiators which are "built-in LED modules with a built-in control device" [13]. Photometric techniques, metrological concepts and lighting characteristics of illumination devices are applicable to HICs in accordance with GOST [13].

The relevance of CISs based on HIC increases with new trends of architecture and of buildings with limited natural illumination (sporting, shopping, civil, industrial, agricultural buildings and underground spaces associated with new urban policies). Large new build projects usually fail to provide for effective natural illumination solutions when meeting microclimate requirements. Standard solutions for light openings (vertical windows, skylights, transparent roof) fulfil standard requirements for illumination but do not solve the problem of optimising the room's energy balance. A suitable alternative to a standard light opening is a HIC based on HTLG, which has the advantages of lighting- and heat-engineering characteristics [14–16]. Development and introduction of CISs based on HICs is an important step in the evolution of high-quality and energy-effecient illumination technology. Each HIC component is simultaneously autonomous, and interdependent, and its energy saving capabilities provide critical efficiencies to the complex:

- Natural illumination based on HTLGs – (50–75) %;
- Artificial illumination of a high energy efficiency based on LED light sources – (20–70) %;
- Automatic control system – (30–70) %.

A Review of CISs and Development of the Concept

In its primitive version, CISs are present at any room with an outside outlet, because they contain at least two components: a system of natural illumination (vertical or top light openings) and illumination devices (ID) of artificial light. These CISs operate along natural light cycles, and their efficiency depends completely on the parameters and quality of the light openings, on efficiency and rationality of the ID. For such systems, low efficiency IDs and their irrational use due to a lack or randomness of control are typical.

As an example of a first attempt to implement a computer-controlled CIS, a combination of roof lights and luminaires with fluorescent lamps can be considered [3]. With an obvious imperfection, such illumination systems nevertheless produce an energy saving effect and confirm the benefits of the CIS concept.

A large-scale project of a heliostat-and-light guide illumination system of a school recreation halls in Saint-Gallen, Switzerland (the *Heliobus* system) demonstrated the huge potential of a computer-controlled CIS through the quality of the created light environment and its energy savings [1, 5, 6].

The development of HTLGs with their unique characteristics was a new stage in CIS evolution. Several engineering solutions of HICs based on HTLGs are known: *LED + Solarspot* [10], *Monodraught* [11, 14] and *Solatube M74 Smart LED* [9]. Every solution has its merits and drawbacks but all of them confirm the potential of the integrated illumination system concept, the important advantages of which are an almost complete lack of heat loss and heat input. The latter is an important advantage in comparison with standard light opening solutions.

Application of such HICs as *LED + Solarspot* [10, 17] for office room illumination tangibly reduces power consumption with an almost complete reduction of heat loss and of heat inputs. A feature of the *LED + Solarspot* HIC structure is that

Fig. 1. *LED + Solarspot* hybrid illumination complex (light guide diameter is 375 mm). Installed in 2010 by *Solarspot International S.r.l* Company

its ALU consists of light emitting diodes placed on the external circular contour of the HTLG diffuser (Fig. 1). Disadvantages of the *LED + Solarspot* luminaire are their blinding and perhaps phototoxic effects in office rooms with low ceilings because of a high dimensional luminance of the LEDs, as well as maintenance challenges when installed at height. (Specifications of the five *LED + Solarspot* HIC model types are given in [10].)

The *Monodraught* HICs are similar to the *LED + Solarspot* in their structure of light-emitting diode ALU but the blinding effect is eliminated by the *LuxLoop* LED panels (Fig. 2). However, the *Monodraught* HIC range [11] is limited by the light guide's diameter (530 mm), by ALU power (30 W) and by luminous flux, which is less than 4000 lm. These limitations restrict the application field of these HICs in rooms with high ceilings.

The above described *LED + Solarspot* and *Monodraught* HICs have a peculiar design, which is not favoured by all users, and the luminous body geometry changes depending on the time of day. In the day-time it looks like a central disc of the HTLG diffuser, and in the night-time it is a LED ring around the dark diffuser (Fig. 2). During transition periods, luminous parts are the diffuser central disc and the ALU ring surrounding it, which change luminance dynamically. A common disadvantage of these HICs is that the combined illumination is created visually by an observable radiation of two separate light sources: HTLG and ALU, the spectral characteristics and luminance of which are different. Furthermore, a transition from natural light to artificial and vice versa is followed by significant changes of HIC light distribution creating a continuously changing light environment and indoor discomfort. It was likely these limitations which led to the restriction on the use of CIS specified by standard documents: СП 251.1325800.2016 and СП 52.13330.2016.

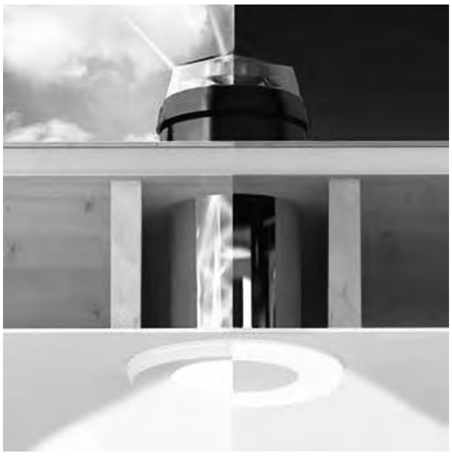

Fig. 2. *Monodraught* HIC. Operating modes under day and night time conditions are shown (the left half of the picture is day-time: natural light penetrates through the diffuser) and night-time, when the LED panel radiates (the right half of the picture: HTLG diffuser as a dark disc)

The *Solatube M74 Smart LED* HIC [9] based on the *Solatube*® HTLG is an optimal structure in terms of lighting characteristics, size, and of design. Blinding and phototoxic effects of the HICs were completely eliminated by a decreases dimensional luminance of the LEDs using diffusers. Depending on room parameters, different diameter *Solatube*® HTLGs and ALUs of different power can be installed. A powerful HIC model based on the *Solatube® M74* HTLG – the *SkyVault* [2] series (tube diameter is 740 mm), deserves special attention as the new generation roof light, providing some advanced solutions beyond those of its competitors. Natural light is very important in buildings with large areas and high ceilings – this supports the application of high efficiency and power CISs.

Advanced features of the *Solatube® M74* HTLG structure and respectively of the *Solatube M74 Smart LED* HIC are its collector and collimator

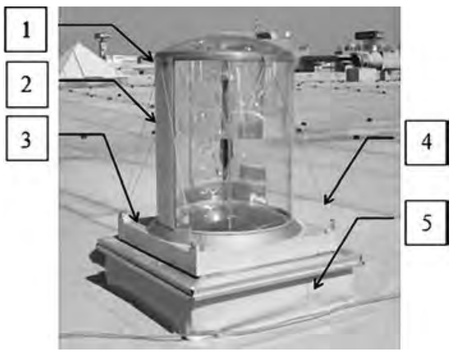

Fig. 3. Input HIC node on the FSC roof:
1 –collector; *2* – *LightTracker*™ reflecting plate; *3* – border flashing; *4* – cable of anti-wind loading; *5* – border

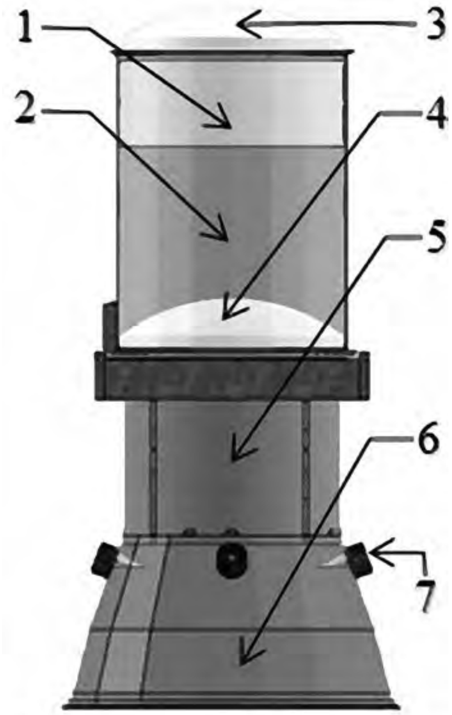

Fig. 4. General view of *Solatube Smart LED* HIC based on HTLG *Solatube® M74*: *1* – collector; *2* – *LightTracker™* reflecting plate; *3* – collector dome; *4* – light guide dome; *5* –light guide tube; *6* – collimator; *7* – LED module, built in collimator.
Complex parameters: collector height is 1067 mm; tube diameter is 740 mm; diffuser diameter is 949 mm; collimator height is 600 mm; tube potential length is up to 30 m; installation height is from 6 to 20 m; luminous flux of the natural light is 18–35 klm; luminous flux of the artificial light unit is up to 9700 lm

[9]. The collector (Fig. 3 and 4) considerably expands the captured area increasing the efficiency of light collection. It is a cylinder made out of transparent material. In the collector, on the inner surface of the semi-cylinder, the *LightTracker™* plate with the *Spectralight® Infinity* high-reflecting coating is placed. In comparison with systems without collectors, the collector optical cylinder increase triple light collection, because of the large area of the reflecting plate equal to 1/2 area of inner side surface of the cylinder and its large volume.

The cone-shaped collimator of the *Solatube® M74* HTLG [2, 9] is convenient for placing an ALU, which in the *Solatube M74 Smart LED* HIC structure consists of four radiating elements built into the collimator plates (Fig. 4 and 5).

In HICs of any structure, the basic element is the HTLG, which is a finished industrial product brought to perfection. Having analysed different models of HIC by leading manufacturers, we selected the *Solatube M74 Smart LED* HIC as an analogue for development of domestic *Solar-LED* HICs, and a project of FSC illumination reconstruction using the *Solar-LED* was developed.

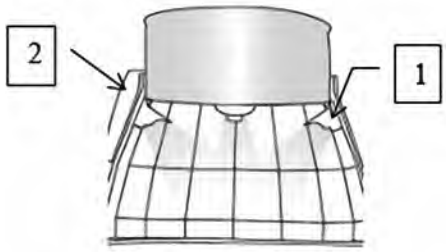

Fig. 5. A layout of placing four radiating elements (LED modules) of *Solatube Smart LED* HICs on the inner surface of the collimator and special transparent caps lenses *1* directing light to the diffuser plane. On the collimator external surface *2*, power supply and control units, as well as cooling radiators of the specified elements are installed

Fig. 6. The illumination system before reconstruction – permanent artificial light IDs. Light sources are HP MHLs

Initial State and Characteristics of the Lighting System

Before the reconstruction, the project's 1920 m^2 area was mainly illuminated with artificial light IDs of 6.6 kW installed power containing bell-shaped luminaires with MHLs of average illuminance ≤ 140 lx (Fig. 6). Natural illumination added ≤ 20 lx and came from four roof lights.

The reconstruction specifications required the following:

– Increase of average illuminance of the combined illumination at the entrance area pier level of the Ashan shop FSC up to 300 lx (in day-time mainly from natural light);

– Maintaining illumination at a constant level during the FSC's full working hours by means of an ACS;

– Support of good colour rendition (R_a > 80);

Fig. 7. A hall view after illumination system reconstruction using *Solar-LED* HICs

– Increased energy efficiency compared with the baseline MHL IDs, up to 60 %;
– Increased reliability and durability.

Design Solution

The solution solved the problem of illumination fo the object using eighteen *Solar-LED* HICs (Fig. 7). Structurally the HIC unites the *Solatube M74* hollow tubular light guide, a LED unit of the preset power artificial light, an ACS (including a light sensor, a controller, a controlled power supply unit of the LED modules) and a fixture for HIC assembling and for fastening functional units around the collimator (Fig. 8). The installed CIS design parameters are given in Table 1.

HIC Efficiency Factor

A parameter was introduced which allows estimating the economic efficiency of an illumination system, in order to evaluate the costs and efficiencies of the CIS at the design stage and inform a reasoned decision. This parameter is especially important, as the published works [1–8] dedicated to HICs do not discuss parameters needed to estimate CIS economic efficiency. This is a normal situation arising as a rule: when describing innovation products or technologies, one should move away from standard terms and definitions. This is connected with the fact that luminous efficacy being a standard evaluation factor of energy efficiency of an illumination device do not describe in full all innovation properties of the product. The CISs and their components HICs are such new products in the light engineering field.

Hence, to evaluate energy efficiency, it is proposed to adapt for inner illumination the relative specific power factor of utilitarian external illumination device according to СП 52.13330.2016. The formula for calculation of CIS average annual relative specific power based on HIC, taking into account a specific character of the component operation, can be expressed as:

$$D_p = P_r \cdot K_d \,/\, (E_{ni} \cdot A),$$

where D_p is the average annual relative specific power of an illumination system, W/(m^2 · lx); P_r is rated power of an illumination system, W; K_d is average annual coefficient of ALU light-emitting diode power demand; E_{ni} is normalised illuminance on the working surface (it has a constant value maintained

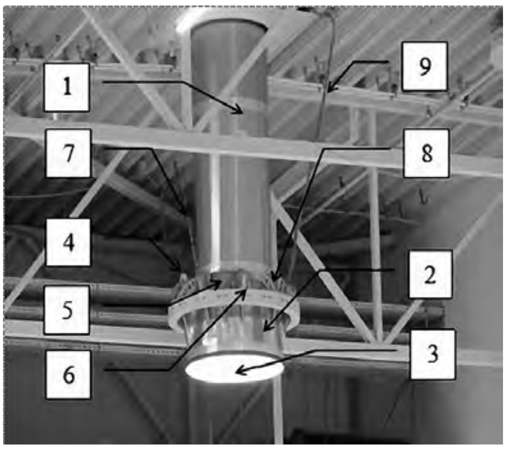

Fig. 8. *Solar-LED* HIC in the FSC:
1 –*Solatube®M74* tube; *2* – collimator; *3* – diffuser luminant disc; *4* –illuminanse sensor; 5 – LED module power supply unit; 6 – assembly ring; *7* – suspension cable; *8* – reinforcement and joint ribs of the collimator with the assembly ring; *9* – power supply and control cables

Table 1. Design Factors of the CIS Object

<table>
<tr><th colspan="3">Factor name</th><th>Factor value</th></tr>
<tr><td colspan="3">Calculation rated capacity (installed power) $^{\#}$, P_{inst}, kW</td><td>max. 9.45</td></tr>
<tr><td colspan="3">Applicability for emergency illumination</td><td>4.9</td></tr>
<tr><td colspan="3">Repairability of HIS ****</td><td>0.30–0.45</td></tr>
<tr><td colspan="3">Electric power of ALU HIC, P_{HICmax}, W</td><td>max. 500</td></tr>
<tr><td colspan="3">HIC Power factor (cosφ)</td><td>0.95</td></tr>
<tr><td colspan="3">Electric power supply circuit</td><td>220/380 V, 50 Hz</td></tr>
<tr><td colspan="3">Controllability of HIC (interval of luminous flux change),%</td><td>(0–10) – 100 compatible with ACS</td></tr>
<tr><td colspan="3">Energy saving effect **,%</td><td>≥ 60</td></tr>
<tr><td rowspan="3">Luminous flux of the complex</td><td colspan="2">HTLG (natural), lm</td><td>max. 35000</td></tr>
<tr><td colspan="2">LED ALU (artificial), lm</td><td>max. 49000</td></tr>
<tr><td colspan="2">HTLG + ALU + ACS*** (combined), lm</td><td>≥35000</td></tr>
<tr><td rowspan="3">Average illuminance of the object</td><td colspan="2">HTLG (natural), lx</td><td>≥300</td></tr>
<tr><td colspan="2">LED ALU (artificial), lx</td><td>≥300</td></tr>
<tr><td colspan="2">HTLG + ALU + ACS*** (combined), lx</td><td>≥300</td></tr>
<tr><td colspan="3">Quality of colour rendition in ALU mode, R_a / T_c</td><td>> 80 / 3500–4000 K</td></tr>
<tr><td colspan="2" rowspan="2">Lifetime, years/hours</td><td>HTLG</td><td>30</td></tr>
<tr><td>LED ALU</td><td>10 / 50000</td></tr>
<tr><td colspan="2" rowspan="2">Warranty operation period, years</td><td>HTLG</td><td>10</td></tr>
<tr><td>LED ALU</td><td>5</td></tr>
<tr><td colspan="3">ALU protection degree from external environment exposure, IP</td><td>42</td></tr>
<tr><td colspan="3">Operation temperature interval, ˚C</td><td>- 20 – + 40</td></tr>
<tr><td colspan="3">Applicability for emergency illumination</td><td>Yes</td></tr>
<tr><td colspan="3">HIC repairability ****</td><td>High</td></tr>
<tr><td colspan="3">Control mode</td><td>Automatic</td></tr>
</table>

Notes:

Due to natural light, the power demand coefficient in the illumination system is equal to 0.30–0.45. Therefore, power consumption decreases more than twice in comparison with the baseline;comparison with IDs with MHL luminaires; ***during the periods of natural illuminance decrease lower than 300 lx;**** The HIS has unit (block) structure; #according to Table 2.*

Table 2. An Example of D_p Calculation for Various Illumination Installations

<table>
<tr><th>ID type</th><th>P_r, kW</th><th>K_d</th><th>E_{ni}, lx</th><th>A, m^2</th><th>T, h</th><th>t, h</th><th>$D_p \cdot 10^3$, W/(m^2·lx)</th></tr>
<tr><td>CIS based on HIC</td><td>9.45</td><td>0.3</td><td rowspan="4">300</td><td rowspan="4">1920</td><td rowspan="4">4380</td><td>1230</td><td>4.9</td></tr>
<tr><td>IDs with LED luminaires</td><td>12.6</td><td rowspan="3">1</td><td rowspan="3">4380</td><td>21.8</td></tr>
<tr><td>IDs with MHL luminaires</td><td>16.5</td><td>28.6</td></tr>
<tr><td>IDs with IL luminaires</td><td>137.5</td><td>238.7</td></tr>
</table>

by ACS at a preset level), lx; A is area of the illuminated surface, m^2.

K_d value is determined as

$$K_d = (1/T)\int_0^t k_d(\tau)d\tau,$$

where k_d is light-emitting diode ALU power demand coefficient changing in time dependent on the object natural illumination level and set by ACS from 0 to 1; t is use duration of the CIS artificial component during a time cycle, h; T is CIS use duration during a time cycle, h.

The D_p calculation technique assumes determining the annual resource of natural light within the location according to meteorological observation data, its change over time, as well as an operation schedule for the HIC artificial component. Calculation parameters of average annual relative specific power for the described object (MEGA Adygeya FSC) for various illumination systems are given in Table 2.

Implementation of the CIS Project Based on Hybrid Illumination Complexes

In December 2016, the upgraded CIS with the reached design parameters was commissioned (Fig. 7). The light environment parameters of the installation (as of April 2017) are as follows: average horizontal illuminance E_{av} = 493 lx and illuminance uniformity coefficient $E_{min}/E_{av} \geq 0.4$ during the daytime, natural E_{av} in fine weather were ≥ 400 lx. The ACS monitored natural E_{av} outside changes depending on the weather and time of day maintaining the design E_{av} level for the combined illumination inside the FSC so that it would be more than 300 lx. Input node and appearance of the HIC with mounting elements, general view of the FSC roof (with installed collectors and HIC) respectively, are shown in Figs. 3, 8 and 9.

Fig. 9. General view of the FSC roof

The CIS ACS is functionally separated into seven groups (there are from 2 to 4 HICs in a group) according to the illuminated area zoning principle. Within the groups, a group control is included. ACS of each group consists of the *DALI-Sensor02 5DPI 41sr* light sensor with remote control, a controller and the HIC ALU controlled power supply units for light-emitting diode modules. ACS adjustment is performed for a HIC group using radio link after the illumination system is mounted.

After the IDs are switched on, the ACS reaches an equilibrium and provides a constant standard illumination level of the space.

To provide the rooms with systems of emergency and evacuation illumination, three HICs are included in their operative circuits. During the light part of a day, CIS HTLGs provide comfortable illumination in case of the FSC electric power supply emergency conditions.

Energy savings are achieved due to a greater luminous efficacy of the light emitting diode ALU than of luminaires with MHLs and because of a decrease of ID power demand coefficient (Table 2) owing to an effective use of natural light.

A comparative analysis[2] of the CISs based on HICs and of light opening standard solutions of upper natural illumination for the implemented project in the MEGA Adygea FSC has revealed higher light- and heat-engineering characteristics of HICs and their indisputable advantage both during warm year period (small solar radiation heat input), and in cold period (low thermal losses).

In the process of implementing a pilot project of the combined illumination system based on the HICs, the experience of designing and installing a hybrid illumination systems was obtained, which has allowed developing a new HIC series[3] free from the disadvantages of the first. The most tangible disadvantage of the implemented CIS is a bright glow of the collectors because of a high level of the reflected light. According to the calculations it is about 22 %. This is an indicator of the ALU optical path imperfection. Another disadvantage of this CIS is the challenge of installing and servicing the HIC, as the ALU and ACS diffusers are mounted high.

CONCLUSION

The conceptual solution of CISs based on HIC structural construction proposed in this article has many advantages compared with traditional systems of general artificial illumination and with the standard openings for natural light. High quality and efficiency parameters and the holistic solution are prerequisites for a widespread introduction of HICs into illumination systems, where the main determining factors are light comfort and energy savings. Based on an analysis of HIC models by leading manufacturers, as comparator for domestic HICs, the *Solatube M74 Smart LED* HIC was selected. Based on its designed structure, a domestic *Solar-LED* HIC was created, and illumination project was developed to illuminate MEGA Adygeya FSC rooms. The project implementation phase has confirmed the main design parameters of the illumination system and revealed some disadvantages, which allowed formulating principles of designing new and improved HICs.

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[2] A separate article of the authors, which will be published in one of the next issues of the journal, is dedicated to the full engineering-and-economic feasibility of HIC application as an alternative to standard traditional light openings.

[3] The authors prepare for publication in the journal an article about new upgrades of HIC high efficiency, of their classification and mounting and operation universality.

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