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Scientific Editors:

Light & Engineering” is an international scientific Journal subscribed to by readers in many different countries. It is the English edition of the journal “Svetotekhnika” the oldest scientific publication in Russia, established in 1932.

Establishing the English edition “Light and Engineering” in 1993 allowed Russian illumination science to be presented the colleagues abroad. It attracted the attention of experts and a new generation of scientists from different countries to Russian domestic achievements in light and engineering science. It also introduced the results of international research and their industrial application on the Russian lighting market.

The scope of our publication is to present the most current results of fundamental research in the field of illumination science. This includes theoretical bases of light source development, physiological optics, lighting technology, photometry, colorimetry, radiometry and metrology, visual perception, health and hazard, energy efficiency, semiconductor sources of light and many others related directions. The journal also aims to cover the application illumination science in technology of light sources, lighting devices, lighting installations, control systems, standards, lighting art and design, and so on.

“Light & Engineering” is well known by its brand and design in the field of light and illumination. Each annual volume has four issues, with about 80–140 pages per issue. Each paper is reviewed by recognized world experts.

To promote the work of the Journal, the editorial staff is in active communication with Thomson Scientific (Citation index) and other international publishing houses and agencies, such as Elsevier and EBSCO Publishing.

CONTENTS

VOLUME 26 **NUMBER 1** **2018**

LIGHT & ENGINEERING

Light & Engineering
Vol. 26, No. 1, pp. 4-6, 2018

Svetotekhnika
No. 1, 2018, pp. 4–6

LIGHT & ENGINEERING / SVETOTEKHNIKA JOURNAL: A REVIEW OF 2017 AND LOOKING FORWARD TO 2018–2020

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2017 has been a very productive and interesting year for our journal Light & Engineering/Svetotekhnika. It was marked by the publication of a large series of analytical reviews on the current state and prospects for the development of a number of important areas of lighting engineering (a total of 12 reviews), the publication of the regional volume of the Light & Engineering Journal (No. 3) devoted to solar energy technology in China (250 pages, 33 articles), further expansion of publications by international authors in Light & Engineering (since 2010, 120 articles by 230 authors from 23 countries have been published).

The journal's editorial board acted as a co-founder of the newly formed branch Industrial Scientific and Technical Council (ISTC), and members of the journal's management became the vice-chairman of the ISTC and chairmen of two important sections within the ISTC.

A new concept for restructuring the work of the journal going forward was developed, published in the journal, and distributed to all members of the editorial board. In the framework of this important programme of work, the journal's website is undergoing major revision. This initiative is enabled by support of our general partner – the international holding company "Boos Lighting Group". In the course of this work the concept of the combined Light and Engineering / Svetotekhnika Journal was formed with two editions in Russian and English languages, a single editorial board for the publication was created, a group of co-founders of the journal was formed within the Academy of Electro-technical Sciences of the Russian Federation (AES RF), the All- Research Institute of Lighting Engineering (VNISI) and the National Research University "MEI".

The main emphasis of the ongoing restructuring is shifting the centre of activity towards further development of the English version of Light & Engineering, making it the scientific core of the journals published in tandem, whilst enhancing the international character of the publication.

Currently, the mission of our journal is the development of light science, as defined within the boundaries of beam photometric representation s [1,2,3] and the varied application of outcomes: for comfortable lighting, for technological processes, including solar energy, for space and ocean exploration, for disinfection of water and air, for medical purposes, and so on. We define lighting engineering as a field of science and technology, the subject of which is the development of methods of generation, spatial redistribution of optical radiation, as well as its transformation into other types of energy and use for various purposes.

The XXI century is the age of light; UNESCO has declared an annual International Day of Light each May 16th. Fields of application for light are continuously expanding. The presence of a single international scientific and technical journal allows us to consider the fundamental theoretical and applied problems with diverse origins, including the use of light in production, recreation, and daily life, from a unified scientific position. The journal is the only publication in the world, which considers issues of lighting alongside questions of using light for technological purposes within the theory framework of the light field. The critical role of light is evident in the fact that more than 15 % of all generated electricity is used for lighting, which rises to up to 20 % in megacities. Publications on the use of light in highly specialized journals of other scientific and technical areas outside the unified positions of ray representations lead to the creation of varied, duplicative terminology systems, and findings that have long since been derived in other areas.

The journal is included in all the key global science databases, such as Scopus, Web of Science and Russian Science Index; well represented and connected on a national and international scale. The journal is included in the list of publications recommended by the Higher Attestation Commission of the Russian Federation for the publication of scientific and technical results of dissertations.

Within the conceptual framework of the two forms of the publication, the English-language form "Light & Engineering" should become the core scientific part of the international publication on the theory of the light field in the photometric description [1–7] and all its possible applications in practice. The Russian-language part "Svetotekhnika" should become a national component fulfilling the role of a national body and serve the purposes of the development of Russian scientific terminology, Russian education, training of scientific personnel, broad exchange of experience in energy saving and labour costs reduction, efficiency gains in all spheres of production, issues relating to the development of the Russian domestic lighting industry.

We prepared and sent letters to members of the International Editorial Advisory Board to find out their views on concept for restructure and secure their support in case of agreement in principle. It gave us great pleasure to hear that almost all international members of the Editorial Board supported our initiative, including, most importantly, the two former CIE presidents. In accordance with this, letters of proposal were prepared and sent to establish partnership relations with CIE National Committees in eight countries which do not have their own regular scientific and technical publications on our subject (Argentina, Brazil, Greece, Turkey, India, Israel, South Korea and Iran). In parallel, authors from these and other countries, who frequently submit articles to our journal were approached with letters seeking their support for our proposal to the CIE national committees in their countries, as well as the proposal to establish correspondent outposts in these countries. Some doubts about the possibility of implementing our programme were expressed and discussed.

Through our partnership offers, we intend expand the publication of various types of articles focused on the state of lighting in these countries in exchange for the National Committees' and correspondents' assistance in selecting and recommending authors and articles from these countries and promoting subscription to our issue in their countries.

At the same time, the journal's leadership put forward the idea of creating a committee or working group on lighting in the press at the CIE secretariat in Vienna, which could include the editors-in-chief of the main scientific and technical journals. This could make the work of all CIE offices more open, with the help of journals it will be possible not only to inform all lighting specialists in different countries about the work of the CIE, on the recommendations issued, technical reports and standards, but also to involve these specialists in discussing draft documents of the technical committees at the stage their development. To test our proposal, we approached the editors of key publications (two in the USA, two in the UK, one in Germany, France, Japan and the Czech Republic) with the principle elements of our proposal; we hope for the support of these highly respected publications. The first positive response from England has already been received.

In August, the editorial staff prepared to participate in a three stage contest for state funding support of professional publications for the period 2018–2020, which was announced by the Russian Ministry of Education and Science. At the first stage, the Ministry of Education selected 500 journals out of 2500. After the second stage only 100 journals remain in the contest. And from this hundred 70 winners are selected at the third stage. It is gratifying that the first stage of the competition in November was a success for our publication.

In the documents prepared for submission to the competition, the following important problems addressed by the journal, the scope of its activities and its main mission for today and for the future were clearly formulated.

The most important tasks facing our publication are:

1. To turn the tandem of our journals into an important centre of publication and expertise, publishing materials devoted to light as a fundamental factor of human society. To disseminate the achieve-

ments of Russian lighting engineering science on an international scale;

2. Expanding the topic coverage of the journal, by publishing articles on the theory of the light field and its applications in lighting, technology and medicine;

3. Ensuring the international status of Light & Engineering / Svetotekhnika by establishing links with the National Lighting Committees of various countries (primarily those without their own scientific issues in lighting) in selecting and reviewing the articles of the authors of these countries, as well as expanding subscription to the journal;

4. Promoting light knowledge through the creation of a virtual publishing hub "House of Light", a centre for the propagation of knowledge about light, its nature, the role of light in human life, the methods of its effective use, the main scientists and inventors, who made a significant contribution to the development of light science and the technology of its use, and to promote the knowledge on light through the journal's website and social media, including Facebook, Twitter, VK, Mendeley, Research Gate, Instagram, and YouTube;

5. Conducting regular reader conferences in Russia and abroad, presenting the journal at international exhibitions;

6. Participation in conferences, including organisation of stands and round tables, as well as the publication of specialized custom issues of the journal in various areas of lighting technology to expand the influence of the publication and improve the economic situation;

7. Exploration of the possibility to establish a Coordinating Committee for Lighting Press under the leadership of the International Commission on Illumination (CIE);

8. Ensuring the active role of the journal in lighting engineering higher education;

9. Creation of awards for the best scientific or design work in the field of lighting;

10. Introduce a bonus system for the best authors and reviewers;

11. Publication of customized analytical reviews by leading specialists in current areas of lighting technology;

12. Creation of a site in two languages with Open Journal Systems (OJS);

13. Increase the annual volume of the Russian version of the publication to ten issues per year, the English version – up to six.

Each article published in the journal undergoes an obligatory "double blind" review, which guarantees a high scientific level of publications.

We hope that the implementation of this large programme of work will occupy the new year for 2018, but will also provide a number of important results for the further development of the Light & Engineering/Svetotekhnika Journal in 2019.

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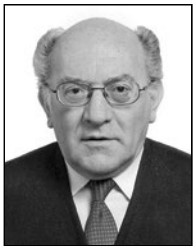

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TECHNOLOGICAL LIGHTING FOR AGRO-INDUSTRIAL INSTALLATIONS IN RUSSIA

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ABSTRACT

The paper gives a review of the current state and future development of technological lighting in the main production sectors of agriculture and horticulture in Russia. Current data is given and an evaluation of the effects of lighting on livestock, poultry, fish, mushrooms, and plant productivity is carried out. The practical application of the latest innovations in lighting technology and photo biology is described.

Keywords: lighting in agriculture, photo period, high-pressure sodium lamps (HPS lamps), light emitting diodes (LED) phyto-irradiators, light culture for plants, photosynthetic photon quantities, regulatory base

1. INTRODUCTION

The accelerated growth of agricultural industries is one of main priorities of the Russian state. Over the last several years there has been a steady annual increase of no less than 3 % due to various kinds of state support and large private investments. The development of agricultural industries is driven by innovation: new facilities for rearing livestock, poultry, fish, mushroom and plant-growing farms are under construction; new equipment and high performance technologies are applied.

Electrical lighting plays an important role in every kind of modern agriculture, and especially in greenhouse cultivation.

2. LIVESTOCK AND POULTRY FARMS

Favourable lighting conditions play a major part in creating the necessary microclimate which ensures a normal physiological state and high productivity of animals and poultry, as well as creating optimal conditions for staff operating the farms.

Recommended illuminance levels for livestock and poultry farms were established long ago in the former USSR, based on longitudinal agronomic studies and have not been revised in 20 years. Current norms OSN-AIC2.10.24–001–04 [1] do not differ greatly from a similar document of 1991, which was developed with assistance from VNISI.

Fig. 1. LED luminaires for livestock farms:
a) *INOX LED70*("Lighting technologies"): 67 W, 7000 lm, 5000K; [4]
б) *IronAgro* ("Varton"): 36 /54 W, 4000/6300 lm, 4000 /6500 K [5]

Fig. 2. LED lighting in livestock farm [6]

Fig. 3. LED lighting in pig-breeding complex [7]

2.1. Illumination of cattle farms

The illuminance levels given in [1] relating to animals pens (E = (20÷30) lx) and feeding areas (E = (50÷75) lx) are obsolete and not applied. Modern farms are intensive milking facilities (for several hundred cattle) and beef farms (up to 20–30 thousand cattle) equipped mostly with imported machinery. Together with the equipment, new technologies are coming to farms in Russia, including new lighting.

Studies conducted in several countries in the last 10–15 years, particularly those conducted in Germany, show that light, which is an active stimulant for many biochemical processes, affects the growth, development, wellbeing, fertility, and yield of large horned livestock.

Proper lighting enables the free movement of cows in loose range housing as well as the rational consumption of feed. According to [2,3] for the main production areas, in the drinking trough zones and feeder troughs the illuminance must be (200–300) lx, while in the pens for milking cows, it should be 200 lx. Milking cows need lighting for up to 16 hours followed by 8 hours rest during the autumn and winter period. Following these recommendations can increase the productivity of dairy cows by 8 %.

Obviously, the higher lighting recommendations also improve working conditions for farm personnel.

Radical changes have taken place in cattle farms with regards to the range of available light sources and luminaire products. Although the outdated standard norms still specify filament lamps, fluorescent lamps, and high-pressure mercury lamps using (7–10 years ago high-pressure sodium lamps were seen to be pioneering and achieved good results in farm lighting), LED luminaires have come to the forefront in the last few years. Whilst climate control systems have led to a significant reduction in the concentration of aggressive vapours (ammonium and other substances), a luminaire designed for cattle farms needs to be IP65 protected, and its housing must be manufactured from chemically resistant ABS-plastics or anodized aluminium, and its diffuser – from acryl or polystyrene.

Fig. 1 gives examples of LED luminaires used in new designs for cattle farms, and Fig. 2 shows a picture of a modern farm.

2.2. Lighting in pig breeding farms

The lighting level inside a modern pig breeding farm, Fig.3, varies from 50 lx to 100 lx and even to 300 lx, and the lighting period – from 10 to 16 hours. Given the physiological needs of fattened animals, the general approach is simply to maintain a moderately lit or even darkened environment [8].

Special LED luminaires are used in new pig farms. The luminaires are water and dust-tight, resistant to an aggressive environment and can withstand high pressure water jets when the facility is washed.

It should be noted that the use of LEDs has led to a significant reduction in power consumption in the farms by up to 2 times.

2.3. Lighting for poultry production

A modern poultry farm is a complex of rooms isolated from the outdoor environment with a controlled microclimate, including lighting that provides good physiological conditions for poultry and enables an increase in almost all productive charac-

Fig. 4. LED lighting in poultry complex: a) with floor reared poultry [11]; b) with caged birds [12]

teristics of poultry, an improved survival rate and decreased feed costs.

The effect of electrical lighting on poultry, the reasonable use of the "lighting factor" and its essential features are discussed in [9, 10].

Since poultry birds react negatively to instant on-and-off switching of lighting, there is a need to simulate natural dawn and dusk effects by using intermittent or rhythmically variable lighting. LED luminaires are best suited for this. They are quickly replacing luminaires with incandescent lamps and tubular and compact fluorescent lamps.

At present, about 200 poultry farms have been equipped with LED luminaires, and the total number of LED luminaires has reached nearly one million units. The lighting systems in the farms operate several specific scenarios with intermittent modes. The luminous flux is effectlively regulated within the range 0÷100 % due to pulse-width modulation at a frequency exceeding 300 Hz.

For the floor-reared broilers (Fig.4a) the recommended illuminance level is 45 lx, while for cell-breeding of chickens (Fig.4b) the illuminance level in the feeder areas must reach 100 lx.

The luminaires for poultry farms are usually linear fixtures with the following features: rated power about (10÷12) W, colour temperature T_c = (3500÷5000) K, R_a> 80. For safety reasons the luminaires are operated from the secondary power-supply units having direct output voltage of 24V, 36V, or 48V.

"Technosvet Group Ltd.", the leading company in poultry farm lighting, states that the use of LEDs will reduce electricity costs by 10–12 times compared with the usage of incandescent lamps and 1.5–3 times compared with fluorescent lamps [13].

3. LIGHTING FOR AQUACULTURE

The term "aquaculture" refers to commercial fish farming in inland ponds or factory pools, or specially created marine plantations. First developed occurred in the 1980s in Norway as intensive production, modern day aquaculture is a platform for the application of effective knowledge-based technologies, including electrical lighting. Norwegian salmon, salmon, and sturgeon, carp and other fish species are produced in aquaculture conditions.

Ambient light is a key factor for fish rearing as it synchronizes all life stages of growth and development. Visual (photo taxis) and non-visual (circadian biorhythm) reactions controlled by spectra,

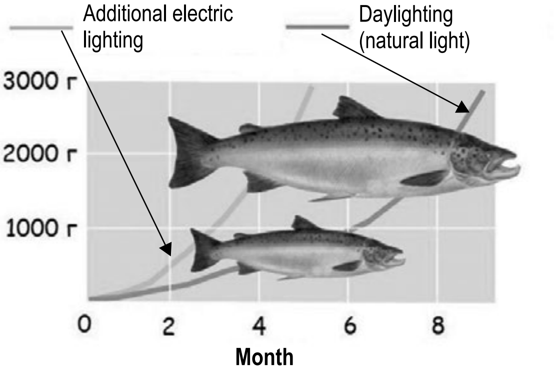


Fig. 5. Light stimulation effect in fish farming [16]

Fig. 6. Lighting in a fish farm [17]

Fig. 7. Lighting in aqua farm using a submersible fixture [18]

lighting level, and photoperiod determine fish behaviour. Operating a light source over the surface of the pool (at a fish factory) or submerged (at an aqua farm) is perceived by the fish as a continuous "light day" and becomes a signal for active feeding, leading to more rapid weight gain, accelerated growth and development, improving the quality of the products [14, 15]. As in humans, the coming of darkness dramatically increases the production of melatonin in fish and suppresses its activity. The achieved effects can be quite significant (Fig.5) which justifies makes necessary the application of special luminaires with HID or LED. At a fish factory artificial lighting is used almost all year round (Fig.6), while at aqua farms in sea cages (Fig.7) it is used mostly during months with a short light day.

Light stimulation is most effective during the early stages of fish development [15]. The following recommendations were formulated as a result of a series of studies:

– For tilapia: illumination on the surface of a pool E_s= 600 lx, lighting duration – $\tau_\text{ф}$ = 12 hours [19];

Fig. 8. Oyster mushrooms farm [24]

– For young sturgeon: $E_s \leq 800$ lx; $\tau_\text{ф}$ = 12 h, it is preferable to use a green radiator [14];

– For young carp: E_s = 20 lx; $\tau_\text{ф}$ = 20 h [15].

Aquaculture is one of the most attractive sectors for investments abroad. The production of farmed fish over the last 30 years has increased 12 times. Studies on the more subtle mechanisms of lighting stimulation and new technologies of growing seafood are being carried out in the USA, Norway and other countries. In Russia, aquaculture began to develop in the last 3–5 years, and the potential of using lighting in this area is significant.

4. LIGHTING IN FUNGICULTURE

The industrial scale growing of mushrooms in specialised indoor facilities is undergoing an active revival in Russia (by 2020 mushroom production of mushrooms should increase twelvefold compared to 2013), it is worth considering this field as of interest for lighting research and trade.

Mushrooms are a valuable source of high-quality and environmentally clean protein; hence their intense indoor cultivation. Champignons, oyster mushrooms, shiitaki and other mushrooms with an average annual yield of 300 kg/m^2 are being industrially grown in facilities with a strictly controlled climate (t = (13÷20) °C, humidity of (85÷90)%, low CO_2 content).

Mushrooms are not phototrophic organisms, which transfer optical radiation into an organic substance (energy). Nevertheless, light is a morphogenetic factor for most kinds of mushrooms, since it provides photo-regulation of their metabolism, affecting productivity. Issues of photo-regulation in mycelium and in the growth of mushrooms are rather complex and so far have not been systematically researched, but have been studied actively in recent years [20]. It is known that chromoproteins in mushrooms serve as light sensors sensitive in the blue part of visible spectrum (flavin), and in the red part – phytochrome, which is similar to the receptors of higher plants.

It is assumed that significant effects increasing productivity could be achieved by using blue radiation with λ = (430÷470) nm [21].

The results of photobiological studies, including those on molecular level, find practical application in agricultural production. Special tests confirm that visible radiation (both illuminance level and duration of illumination) activates the growth

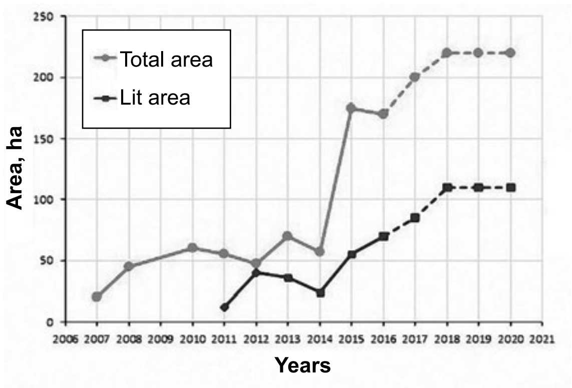


Fig. 9. Construction of new greenhouses in Russian during the last ten years and forward to 2020

processes, in particular, in oyster mushrooms, by affecting formation of bodies and productivity [22]. An illuminance level of (150÷200) lx (white light) for a photoperiod of 10–12 hours during the whole cultivation period is currently used in oyster mushrooms cultivation technology on one of the production farms (Fig.8) [23].

At the same time, it has also been demonstrated that with an increase in illuminance level up to 1000 lx for 12 hours daily lighting duration the yield of oyster mushrooms can increase by (25÷30) % [20].

Based on an analysis of a small but relevant amount of experimental and practical data, and considering the planned scale of development, it can be concluded that there are significant opportunities for the use of artificial lighting for industrial mushrooms production, which will make an important contribution to the creation of environmentally friendly technologies for the cultivation of mushrooms, including those with a specified bio-chemical composition.

5. LIGHTING (IRRADIATION) OF PLANTS IN GREENHOUSES

5.1. General context

At present, greenhouse cultivation is one of the fastest growing agricultural industries, and perhaps in the Russian production economy overall.

At the end of 1980s in the former USSR, the total area of winter greenhouses was about 4000 ha, and from the beginning of 1990s steadily decreased: by 2010 it had dropped to 1800 ha. But due to government support and the construction of new flower and vegetable greenhouses, the total area has reached 2300 ha in 2017. By 2020 there are plans to build another 1000 ha and to double the production of greenhouse vegetables. Fig. 9 shows data on the construction of new greenhouses during the period from 2007 to 2017, and gives a forecast up to 2020.

Modern industrial greenhouses in Russia represent a small but very specific sector of the economy, both highly power consuming and energy efficient; about two dozen new technology methods are used in this sector, including the computer controlled cultivation of plants. Lighting is the most important technology in the new greenhouses since it allows the facility to grow plants almost all year round. Fig. 10 shows the distribution of areas between different kinds of plants.

The total annual electric power consumed by the greenhouses in Russia is about 650 MW, the number of light units (mostly luminaires with high-pressure sodium (HPS) lamps of 400W, 600W, and 1000W) exceeds one million pieces. Greenhouse lighting consumes about 1/8 billion kW per hour of electric power, which exceeds the consumption of civic lighting in the cities of Moscow, St. Petersburg, Nizhny Novgorod and Kazan.

Here are the main technical parameters for lighting technology for cultivation: a specific installed electric power range (100÷250) W/m^2 (depending on the type of plant); the duration of lighting per year is up to 5500 hours; illuminance levels are (10÷30) klx; yield is up to 150 kg/m^2 (for example for cucumbers); the average annual energy consumption for 1 kg of product is up to 15 kWh.

The annual capacity of the luminaire market for greenhouses mostly depends on the amount of newly commissioned areas to be lit. In 2017 it may be up to 250–270 thousand pieces. Note that both the rate of construction of new greenhouses with artificial lighting in Russia (Fig.10) and their share

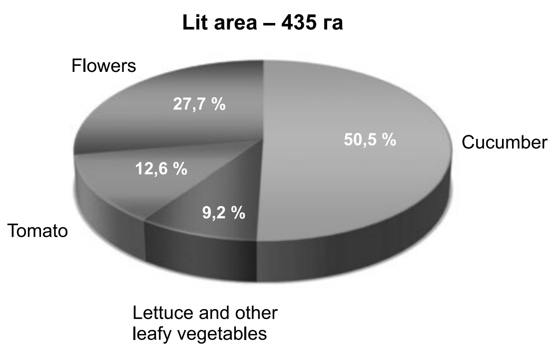


Fig. 10. Area distribution in greenhouses in Russia

Table 1. The main parameters of HPS phyto-lamps in tubular bulbs (P_l – lamp wattage, U_m – mains voltage, I_m – current, taken from the mains, I_l – lamp current, U_l – lamp voltage, P_b – power losses in the ballast, Φ_l – lamp luminous flux, η_v – lamp efficacy, Φ_{PPF} – photosynthetic flux of photons (lamp), η_{ph} – lamp efficiency in PAR range, $Ø_l$ – lamp bulb diameter)

№	P_l, W	U_m, V	I_m, A	I_l, A	U_l, V	P_l+P_b, W	Φ_l, klm	η_v, lm/W	Φ_{PPF}, µmol/s	η_{ph}, µmol/(s ·W)	$Ø_l$, mm
1	250*	220	1,5	3,0	100	285	33,2	132	420	1,7	46
2	400*	220	2,4	4,4	104	445	56,5	140	725	1,8	46
3	600	220	3,4* 2,9**	6,2	112	645* 635**	90,0	150	1100	1,8	48
4	600	380	1,90* 1,61**	3,6*	200	645* 640**	90,0	150	1150	1,9	48
5	1000**	380	2,61	4,0	250	1040	145	145	2100	2,1	32***

* – with electromagnetic ballast; ** – with electronic ballast; *** – in overhead installation

in the general volume of newly built greenhouses are unique in global practice.

5.2. Light sources for greenhouses

Almost all production greenhouses are equipped with "phyto-HPS" lamps. These lamps differ from the conventional HPS lamps by higher pressure of buffer gas that enables a raised luminous efficacy up to 150 lm/W (for 600 W lamps), an increased lifetime and stability of luminous flux, and a slight increase in the fraction of radiation in important for growth and development of plants blue range of photosynthetically active radiation (PAR). The main parameters of phyto-HPS in tubular bulbs are given in the Table 1.

Although the spectrum of an HPS is not considered to be the most favourable for the growth and development of plants, these lamps combined with advanced cultivation techniques have provided high levels of plant productivity. The greenhouses environment is a good example of the combined action of daylight and artificial lighting, therefore, even during the low light time of year (e.g. December), when the share of light provided by artificial lighting is up to 90 %, daylight still makes a significant addition to the total spectrum in the blue part of the PAR, providing the necessary photo-regulation for the plants.

The Russian agricultural sector uses phyto-HPS lamps from leading foreign manufacturers: *BLV* (Germany), Osram (Germany), *Philips* (the Netherlands), *Narva* (Germany), *MegaPhoton* (China). Not the full range of HPS lamps is produced in Russia. "Reflax Ltd." is the largest and most well-known Russian manufacturer of HPS lamps with mirror and tubular bulbs and import discharge tubes. "Lisma" also started to produce tubular phyto-lamps. "BL-Trade Ltd." has organised the production of the most popular types of 600W and 1000W phyto-HPS lamps at a foreign factory under the brand name "Galad".

5.3. Luminaires for greenhouses

The luminaires (phyto-irradiators) for greenhouses must have high functionality and operational characteristics. Only luminaires with an efficacy of (120÷125) lm/W (for 600 W fixtures) can successfully compete in the market with foreign manufacturers. This means that the light output ratio of a reflector should be at (90÷92) %, active power losses in the ballast must be minimal (7.0÷7.5) % (for 600 W fixtures), the luminaire must be durable and long-lasting, with a low weight and an acceptable price.

"Reflux" reflector lamps (lamps-luminaires) have the key part of the luminaire design, i.e. reflector. Due to the use of silver instead of aluminium for the reflective layer, the products have an increased efficiency and are widely used in new greenhouses.

Luminaires, both with electromagnetic (for 250, 400, and 600W) and electronic (for 250, 600, and 1000W) ballasts, are currently available on the mar-

a) ***b)***

Fig. 11. *Galad* greenhouse luminaires [26]: a) JSP30–600–013; б) JSP38–1000–003

ket. The type of ballast determines the faults and benefits of a phyto-irradiator; this is well understood and discussed in detail, e.g. in [25]. Luminaires with electronic ballasts have a low weight and are capable of adjusting the electrical power of a lamp, but they are less reliable and more expensive. On the contrary, luminaires with electromagnetic ballasts are more reliable and less expensive, but heavy. Examples of the most popular HPS luminaires on the market with wattages of 600W and 1000W are given in Fig.11. At least for the current year, the preferences of consumers who are building new greenhouses are distributed equally between two choices.

Hortilux (the Netherlands) and *Gavita* (the Netherlands – the USA – Canada – Norway) are well known and established on the Russian market for greenhouse luminaires. They are in competition with other products by a company with a 45 year history in the production of phyto-irradiators from Kadoshkino (under trade-mark "GALAD") and also by "NFL", "Tochka Opory", and "Reflux Ltd".

5.4. Lighting installations for modern greenhouses

Lighting installations (LI) in greenhouses are cannot be compared to other lighting systems due to their power consumption (more than 2000 luminaires with a rated wattage of 600W are installed per hectare), which is more than an order of magnitude greater than in other high power consumption lighting systems, e.g. sports lighting. Special measures are being taken to improve the utilisation factor of luminous flux (reaching a level of 0.95÷0.97) through the use mirror screens on the ceiling and walls at night time, not only for maximising efficiency but also for the reduction of light pollution in the outside environment.

During lighting design a priority is given to obtaining the optimal ratio between the illuminance level E and the specific installed electric power P_1: $K_{LI} = E/P_1$, which is an indicator of lighting efficiency. Usually, it is at the level of K_{LI} = (125÷130) lm/W.

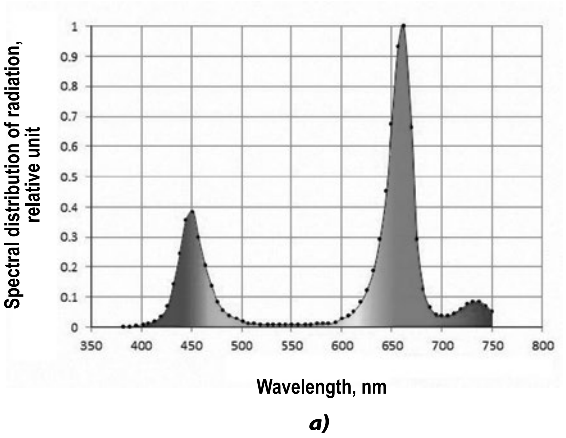
The illuminance must be stable, though there will be some decrease due to a reducing luminous flux of lamps. Our measurements have found that the the reduction in luminous flux for HPS lamps is about (18÷20) % after four years of operation; the calculations take into account the direct dependence of productivity on the illuminance level give grounds to conclude that using lamps further after four years is economically unreasonable [27].

5.5. LED phyto-irradiators for greenhouses

Radical changes in the market for greenhouse lighting have taken place with the rapid development of light-emitting diodes (LEDs) and the replacement of conventional HPS lamp fixtures by LED luminaires. Having reached and exceeded the efficiency level of sodium phyto-irradiators, LED-irradiators also surpassed them by tuning spectral characteristics to match the specific needs of crops and cultivation.

Regretfully, many developers and manufacturers trying to win time and stay ahead of competitors, neglect long and expensive photobiological studies needed to optimise the design requirements for phyto-irradiators. Instead they invent various quasi-scientific approaches in an effort to "fit" the actual spectrum of radiation to the photosynthesis sensitivity spectrum, although it is well known that there is no unified optimum spectrum for all plants.

VNISI takes a different approach, attempting to solve this problem in cooperation with plants physiologists, based photobiological studies and re-



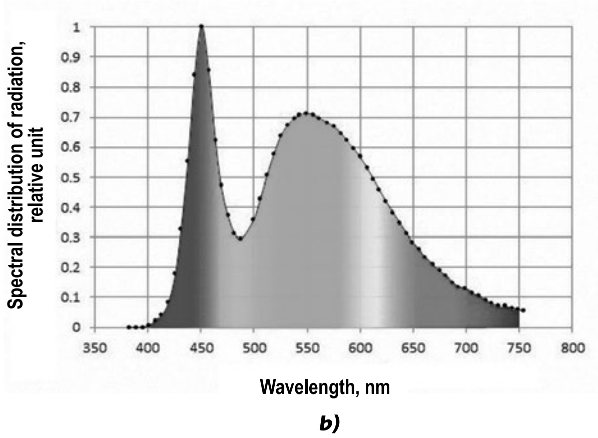


Fig. 12. Typical spectra of LED-irradiators: a) "*doublepeak*" irradiator; б) "white" irradiator

sults which can be applicable in greenhouses [28–31]. Such optimisation could yield energy savings of (30÷35) % if HPS lamps were replaced by LED-irradiators [28, 29].

Currently, the supply of LED-irradiators on the Russian market greatly exceeds demand. Nearly two dozen foreign and domestic companies offer their products. The irradiators comprise LEDs based on either *AlGaInP* or *InGaN* structures that generate red and blue radiation, or *InGaN* structure together with a phosphor that generate full spectrum light. The LED arrays are packed either by *SMD* or *COB* technologies. The LEDs are produced by the leading foreign manufacturers: *Cree* (the USA), *Osram Semiconductor* (Germany), *Lumileds Luxeon* (the USA), *Nichia* and *Citizen* (Japan), etc. Fig. 12 shows spectra of radiation used in greenhouses: Fig.12a shows the "double-peak" spectrum of a red-blue irradiator, and Fig.12b shows the spectrum of a "white" irradiator with correlated colour temperature in the range of 1800K to 6000K.

LED phyto-irradiators are introduced into greenhouses in the following forms:

– Traditional overhead lighting;
– Inter-row lighting;
– Multi-tiered systems for growing plants.

Overhead irradiators are designed to replace HPS luminaires, they may be of rectangular or linear shape, with a wattage from 100W to 600W. Inter-row LED-irradiators are of (35÷160) W, (0.85÷2.50) m long with a specific power of (0.4÷0.65) W/cm (Fig. 13). The LED-irradiator for multi-tiered systems have no alternative, hence their volume of production depend only on the rate of market uptake of innovative phyto-installations like *"City-Farm"* (Fig. 14).

The main reason for the slow penetration of all kinds of LED-irradiators on the greenhouse market is their high cost. Detailed technical and cost analysis shows that the payback period for introducing LED-irradiators is no less than 5–7 years [35]. However, it should be noted that in 2017 the first large project based on LED-irradiators will be realised in one of the Russian greenhouse complexes [36].

5.6. New problems in measuring photosynthetically active radiation (PAR)

The use of LED-irradiators with different spectra (including radiation at the borders of the visible range) made it necessary to introduce a new system for PAR measurement. In the 1960s it a new system was proposed which would account for both the number of photons in the PAR range (λ = (400÷700) nm) absorbed by the plant and the equivalent number of CO_2 molecules resulted due to photosynthesis [37]. Thus, by using recommendations of

Fig. 13. Inter-row lighting system with *Philips LED-irradiators* [32]

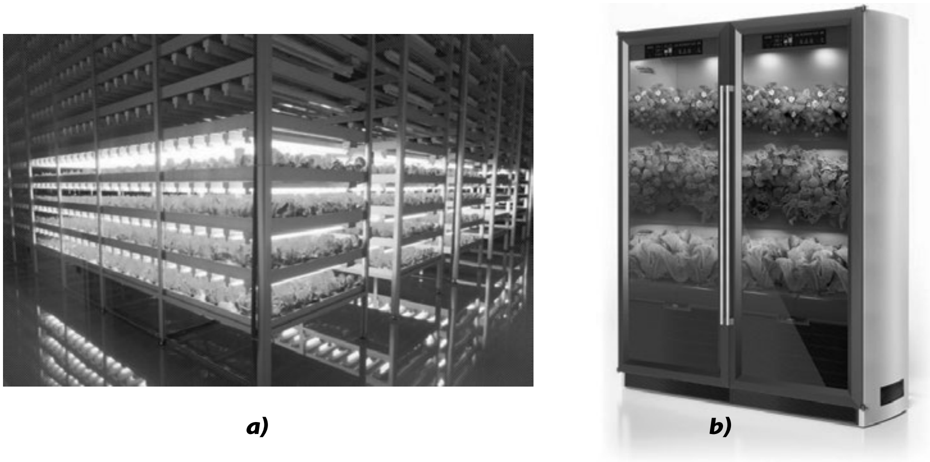


Fig. 14. Multi-stack installation for growing plants with LED irradiation:
a) industrial, "*CityFarm*" type [33]; b) home-scale [34]

*DIN5031, t.1,*1985 [38] and for practical convenience, the ratio of the quantity of photons to the Avogadro number, the unit for measuring photosynthetic photon flux (Φ_{PPF}) in µmol/s was introduced, as well as its derivatives: E_{PPFD} density in µmol/(m^2·s), and η_{PPF} efficacy in µmol/(s·W) or (µmol/J), etc. Several photon values for HPS lamps are given in Table 1.

The photosynthetic photon flux as an effective value may be written in the following canonical form:

$$\Phi_{PPF} = \int_{400}^{700} \Phi_e(\lambda) \cdot S(\lambda) d\lambda,$$

where $S(\lambda) = \dfrac{\lambda}{h \cdot c \cdot N_A}$ is a function of spectral efficiency within photosynthetic photon system of variables, $\Phi_e(\lambda)$ is a spectral density of radiant flux, λ is a wavelength of radiation in the PAR range, h – Planck constant, c –velocity of light, N_A – Avogadro number.

The expression for E_{PPFD} can be written accordingly.

Despite the simple form of a linear function $S(\lambda)$, there are serious metrological challenges associated with measurements of photosynthetic photon values, which warrants a separate discussion.

There are several foreign and locally produced devices [39, 40] for spectral and integral measurements of Φ_{PPF} and E_{PPFD} in Russia. However, none of them is included in the State Register of measuring instruments, since they do not guarantee accurate measurements except for the most simple case, i.e. for an HPS irradiator.

5.7. Norms and recommendations for greenhouse lighting

Development of lighting technology, and the emergence of LED-irradiators increased the importance of creating a regulatory basis for greenhouse lighting. Very little is available now; the only document of an advisory nature describes the problems of greenhouse lighting incorrectly [41].

In 2016 in VNISI, two standards were developed [42–45] related to the regulation and control of the photosynthetic photon flux in production of LED-irradiators and measurements of photosynthetic photon flux density in greenhouses, where in fact a new system of photosynthetic photon quantities was introduced for the first time.

The regulations for greenhouse lighting are being actively developed abroad as well. In July 2017 the United States issued the national standard "Quantities and units of optical radiation for plants". The standard was prepared with the participation of an international group of experts from the American national standards Institute (ANSI) and the American society of agricultural and bio-engineers (*ASABE*) [46]. Several other standards on lighting in greenhouses [47] are under preparation in the United States. We hope similar work will begin in Russia as well.

To conclude this review of what appear to be quite different lighting systems, we would like to note one important general fact: agricultural lighting in Russia, which only 15–20 years ago was based on outdated luminaires and lighting sources (incandescent lamps, T12 fluorescent lamps, high-pressure mercury lamps), has made a significant leap forward and by using the latest lighting technologies is making a significant contribution to the import substitution drive and supplying the population with high-quality food products.

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STANDARDISATION OF LIGHTING FIXTURES AND INSTALLATIONS FOR GREENHOUSES

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ABSTRACT

The article describes standards for industrial greenhouses irradiators (GOST R57671–2017), methods for measuring PAR region irradiance in overhead and rack-type installations (preliminary standard 211–2017), methods for measuring illuminance (FR.1.37.2017.27376) and photosynthetic irradiance (FR.1.37.2017.27375), photosynthetic photon flux (FR.1.37.2017.27374) and other lighting characteristics, energy efficiency factor calculations for LED installations in greenhouses (FR.1.37.2017.27373), which have been developed at VNISI and are unique in world practice.

Keywords: LED irradiating installations, LED irradiators, photosynthetic photon flux, photosynthetic irradiance, illuminance, energy efficiency factors, relative specific power, specific annual power consumption

1. INTRODUCTION

Development of agriculture under artificial lighting has made it necessary to shape the regulatory foundation for lighting in greenhouses. Present norms [1] for the lighting of growing plants are obsolete, as they are representative of the 1990s situation and do not fit the requirements of the present day. Hence new standards and methods need to be created for measuring both the characteristics of optical radiation of modern luminaires with light emitting diodes (LEDs), and of irradiating systems. Such standard documents will prevent fake declarations regarding efficiency of LED-irradiators and support the accelerated penetration of LEDs into greenhouse lighting practice.

Presently, "The guidelines for technological design of greenhouses for growing vegetables and seedlings" [2] is the only normative document in force in Russia, which addresses lighting in greenhouses as well as other design aspects. The document belongs to "the advisory directives of the Ministry of Agriculture of the Russian Federation", but, unfortunately, it treats the nature of the "lighting climate" in greenhouses incorrectly. For instance, paragraph 6.1.4 of the recommendations reads "*for growing seedling under artificial lighting the irradiation level shall be 80 W/m^2 and for vegetables (80 ÷ 160) W/m^2 of photosyntetically active radiation (PAR)*". That means than in case HPS lamps are used the illuminance level should comprise (30 ÷60) klx, which does not reflect reality: the illuminance level in industrial greenhouses just about approaches the lower boundary of given range [3].

In 2016–2017, VNISI developed two standards relating to plant cultivation in covered ground: GOST R57671–2017 "Irradiating Devices with Light Emitting Diodes for Greenhouses, General Technical Terms" [4], and the preliminary standard 211–2017"Irradiation of Plants by LED Sources, Measurements Methods" [5]. The documents were discussed publicly and should come into force on December 1, 2017. The standards introduce for the first time a new system of photosynthetic photon values and attempt to regulate lighting in greenhouses, as similar work on lighting in greenhouses is also developed in other countries [6]. For example, in July 2017 the US issued the national standard "Values and Units of Optical Radiation for Plants". The standard, prepared by the American National Standard Institute (ANSI) and the American Society of Agriculture and Biology Engineers (ASABE) [7] with the aid of an international group of experts, is a volume of terms and descriptions in the field of radiant and photon variables (see [8]) applicable to plant photo cultivation (see [9–12]). Currently, the *ANSI* and *ASABE* are developing one more standard related to lighting of plants in greenhouses [13].

2. GOST R57671–2017 "IRRADIATING DEVICES WITH LIGHT EMITTING DIODES FOR GREENHOUSES, GENERAL TECHNICAL TERMS" [4]

The Russian standard GOST R57671–2017 applies to LEDs luminaires designed to irradiate plants in greenhouses and other facilities with covered ground and an AC power supply with mains voltage up to 600V. The standard comprises general requirements for greenhouse luminaires, including photometric and electro-technical demands, related to design and protection from exposure to climate and a mechanical environment. In the photometric part of the document the performance requirements of the devices in the PAR range are given: minimum is 2.0 µmol/J for lighting the plants from above, and a minimum of 1.8 µmol/J for additional lighting of plants in cenosis (inter-row), and at least – 1.9 µmol/J for illumination of plants in a tiered rack-type installation. The standard gives a short description how to determine efficiency of luminaires in PAR range, comprising the following steps:

– Measurement of spectral density of radiation in PAR range (400÷700) nm;

– Calculation of photosynthetic photon flux using the following expression[1]:

[1] Photosynthetic photon flux may be found by measuring luminous flux and relative spectral radiation distribution. The corresponding technique was developed by VNISI (see. 4.1).

$$\Phi_{PAR} = \int_{400nm}^{700nm} \phi_\lambda \cdot \frac{\lambda}{h \cdot c \cdot N_A} \cdot d\lambda, \qquad (1)$$

where Φ_{PAR} is the photosynthetic photon flux, µmol/s; φ_λ is the spectral density of luminaire radiation, W/nm; λ is the wavelength, nm; h is the Planck constant; c – velocity of light; N_A – Avogadro number;

– Measurement of luminaire power consumption;

– Calculation of luminaire efficiency in PAR range:

$$\eta_{PAR} = \Phi_{PAR}/P, \qquad (2)$$

where η_{PAR} is luminaire efficiency in PAR range, µmol/J; Φ_{PAR} is the photosynthetic photon flux, µmol/s; P is the power consumed by a luminaire, W.

3. THE PRELIMINARY STANDARD 211–2017 "IRRADIATION OF PLANTS BY LIGHT EMITTING DIODES, MEASUREMENT METHODS" [5]

The preliminary national standard 211–2017 defines the methods for measuring the characteristics of irradiation of plants in greenhouses:

When the plants are irradiated from above or in tiered rack-type installations:

– Horizontal photosynthetic irradiation,

– Average horizontal photosynthetic irradiation,

– Uniformity of horizontal photosynthetic irradiation;

For additional irradiation of plants within a cenosis (inter-row exposure):

– Vertical photosynthetic irradiation.

The document describes the methods for measuring horizontal and vertical irradiation in greenhouses. The measurements shall be taken at test points, the location of which depends on the type of installation.

In installations where plants are irradiated from above, the measurements shall be taken in the horizontal plane where plants will sit (but without the plants) within the test area formed by the projections of the centre points of the nine light fixtures (3 × 3). The fixtures shall be selected in such a way that between any of these fixtures and the aisles or the wall of the greenhouse there are at least four fixtures. The region where the test area shall be locat-

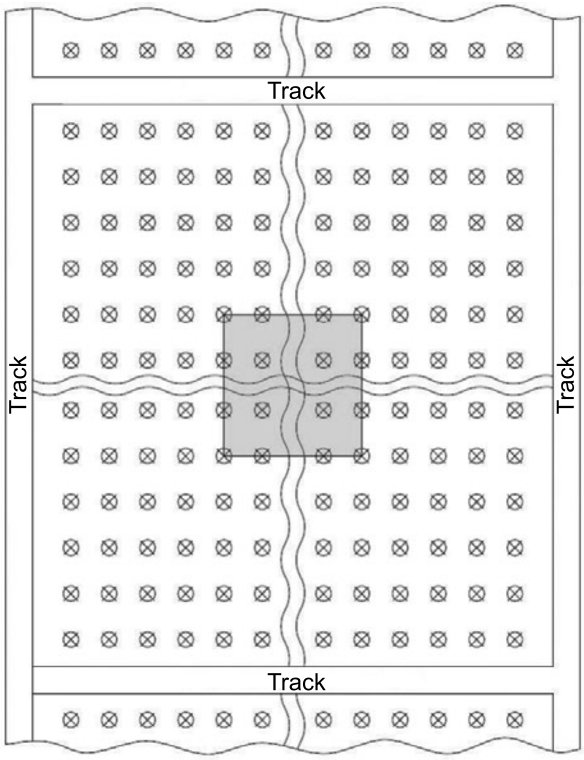

Fig. 1. Location of the test area for measuring horizontal irradiance in installations for irradiating plants from above: ⊗ – projection of the luminaire centre on the plane of measurement; region where the test area should be located is shown as background

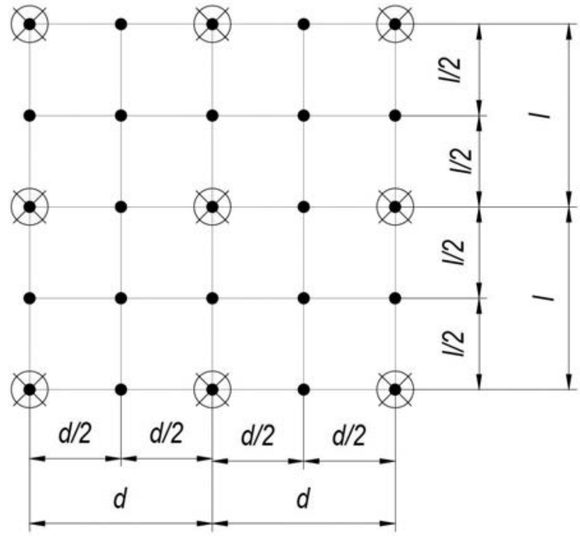

Fig. 2. Layout of test points for the measurement of horizontal irradiance in installations for irradiating plants from above: ⊗ – projection of the luminaire centre on the plane of measurement, ● – test point, *l* – distance between luminaires in longitudinal (parallel to greenhouse axis), *d* – distance between luminaires in cross section (perpendicular to greenhouse axis)

ed is shown in Fig.1. The test points where horizontal irradiance shall be measured are given in Fig.2.

In tiered rack-type installations the measurements shall be carried out for one arbitrary shelf. The measurements shall be taken in the horizontal plane of planting (in the absence of plants) at the test points shown in Fig.3.

For installations with additional irradiation of plants in cenosis (inter-row exposure) the measurements shall be carried out in the vertical plane running through the planting line (in the absence of plants) from one arbitrary side of the aisle plants rows at a minimal distance of $L/10$ from the beginning or the end of planting; where L is the length of plants row. The measurements shall be taken at the test points located as shown in Figs.4 and 5.

4. METHODS FOR MEASURING RADIANT FLUX AND IRRADIANCE/ ILLUMINANCE LEVELS WITHIN PAR RANGE

The development of the standards, the increasing need for metrological support for greenhouses cultivation, as well as the wide application of LED sources for energy savings and optimised light spectrum for plant photosynthesis, have made it necessary to develop methods for measuring such parameters as photosynthetic photon flux of irradiating devices and irradiance/illuminance of plants in greenhouses. Such methods had been developed in VNISI [14–17]. They prescribe the use of the latest techniques for measuring spectral and integral characteristics, which enable to determine the radiant flux and irradiance in the PAR range with acceptable accuracy.

4.1. Measuring photosynthetic photon flux of LED luminaires designed for greenhouses using a goniophotometer "RIGO 801" and spectroradiometer "CAS140" [14]

This method has been registered with the Federal Information Fund for Uniform Measurements under reference number № FR.1.37.2017.27374. It sets out the combination and sequence of specifically described steps, which provide the measurements of photosynthetic photon flux in the range $6x10^{16}$ to $1.8x10^{21}$photons/s (from 0.1 to 3000 μmol/s). Photosynthetic photon flux is determined based on the measured luminous flux in [lm] of LED devices and relative spectral density of the radiation flux in [rel. units/nm] with further mathematical process-

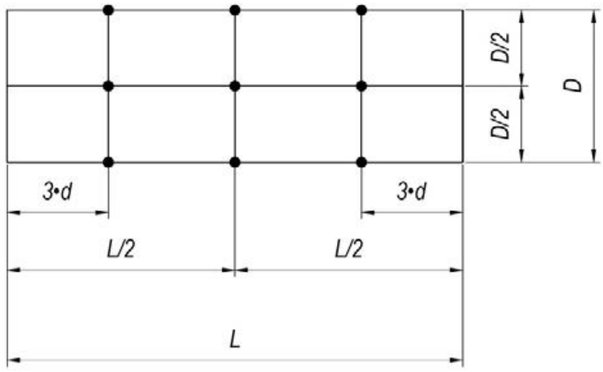

Fig. 3. Layout of test points for the measurement of horizontal irradiance in multi-story rack-type installations: ● – test point, L – shelf length, D – shelf width

ing of the measurement results. The total relative error of measurements of photosynthetic photon flux with the goniophotometer "*RIGO 801*" (manufactured by *TechnoTeam Bildverarbeitung GmbH, Germany)* and spectroradiometer "*CAS140*" (manufactured by *Instrument Systems GmbH*, Germany) is 8.2 % for white LEDs and 10.3 % for red and blue LEDs. For the convenience of users the document contains an algorithm for calculating the photosynthetic photon flux and photon intensity in *Excel* based on measured values of luminous flux and luminous intensity of irradiating fixtures and their relative spectral density of the radiant flux in the (380 ÷780) nm wavelength range.

4.2. The method for measuring illumination of plants with the luxmeter "TKA-LUX" in industrial greenhouses lit with LED luminaires [15]

This method has been registered with the Federal Information Fund for Uniform Measurements under reference number № FR.1.37.2017.27376. It is designed to check whether the illuminance of plants in greenhouse meets the requirements. It sets out combination and sequence of specifically described steps that provide the measurements of illuminance in the range from 1.0 to 200000 lx in the (380÷760) nm wavelength range. Horizontal illuminance is measured at test points prescribed in a draft of the standard 211–2017 with further mathematical processing to obtain an average illuminance and uniformity at the plane for planting. The *Excel* algorithm mentioned in paragraph 4.1 allows to transform the measured illuminance into irradiance levels under a given radiation spectrum of the LED luminaire.

The total relative error of measurements of illuminance with a luxmeter TKA-LUX (TKA Ltd, Russia) is within the range from 6 % to $6 + 2\cdot\Delta h/h\cdot 100$ %, where Δh is the distance between the plane of measurement (measuring surface of luxmeter photometric head) and the plane for planting, h is the height of luminaire suspension relative to the plane for planting. In real conditions, the Δh does not exceed 0.04 m, while the typical suspension height of irradiating fixtures in greenhouses is

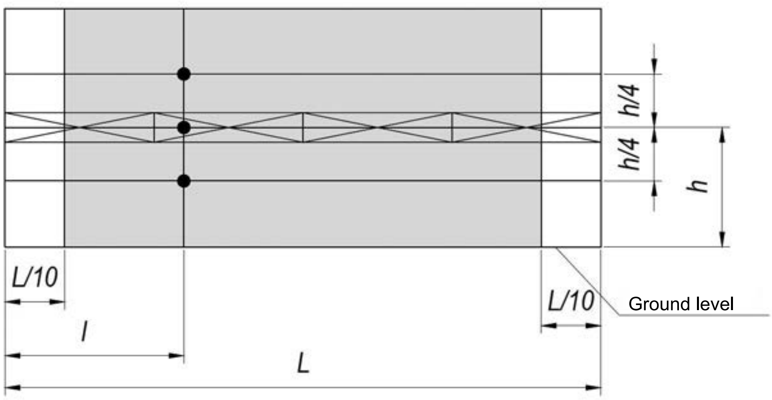

Fig. 4. Layout of test points for the measurement of vertical irradiance under inter-row irradiation of plants from one row of luminaires: [luminaire symbol] – projection of the luminaire on the plane of measurement, ● – test point, L – plants row length, l – distance between test point and the beginning of plants row ($0{,}1\cdot L \le l \le 0{,}9\cdot L$), h – luminaire suspension height above ground level; region where the test area should be located is shown as background

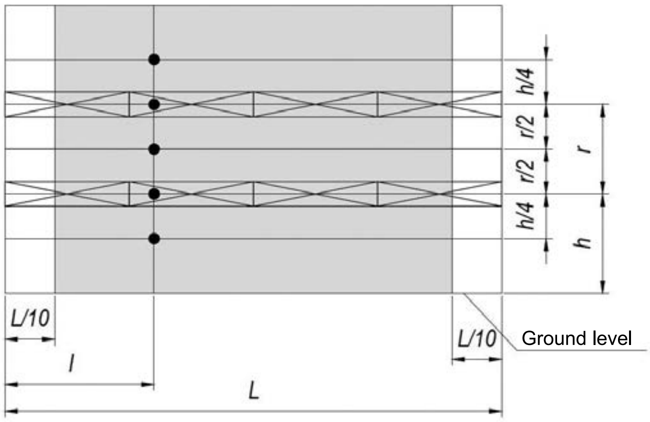

Fig. 5. Layout of test points for the measurement of vertical irradiance under inter-row irradiation of plants from two rows of luminaires: – projection of the luminaire on the plane of measurement, ● – test point, *L* – plants row length, *l* – distance between test point and the beginning of plants row ($0{,}1\cdot L \le l \le 0{,}9\cdot L$), *h* – luminaire suspension height above ground level, *r* – distance between luminaires rows; region where test area should be located is shown as background

over 2 m when lighting the plants from above, and more than 0.8 m in multi-story rack-type installations: thus the relative error of illuminance measurements does not exceed 6 % and 11 % respectively.

4.3. The method for measuring photosynthetic irradiance with quantum sensor "LI-190R" in industrial greenhouses illuminated by LED installations [16][2]

This method has been registered with the Federal Information Fund for Uniform Measurements under reference number № FR.1.37.2017.27375. It is designed to check if the photosynthetic irradiance of plants in greenhouse meets requirements. It sets out combination and sequence of specifically described steps that provide the measurements of photosynthetic irradiance of plants in the range from 6×10^{17} to 1.2×10^{22} photon·s^{-1}·m^{-2} (from 1 up to 19999 μmol·s^{-1}·m^{-2}). The method prescribes the measurements of horizontal photosynthetic irradiance at test points given in the preliminary standard 211–2017 with further mathematical processing to obtain an average irradiance and uniformity at the plane for planting.

Like in paragraph 4.2, the total relative error when measuring irradiance with quantum sensor "*LI-190R*" (LI–COR, Inc., the USA) is between 5 % and $5 + 2\cdot\Delta h/h\cdot 100$ %, and in real conditions it does not exceed 5 % in installations where plants are lit from above and 10 % in multi-story rack-type installations.

4.4. The method for measuring lighting characteristics and calculation of power efficiency of LED installations for irradiation of plants in greenhouses [17]

This method has been registered with the Federal Information Fund for Uniform Measurements under reference number № FR.1.37.2017.27373. It is designed to comparatively analyse irradiating installations at the design stage or in during procurement. It sets out the combination and sequence of specifically described steps that provide the measurements of spatial distribution of luminous intensity of luminaires in the range from 1cd to 150000 cd and relative spectral distribution in (360 ÷ 830) nm wavelength range, as well as the calculation of the average horizontal photosynthetic irradiance in the planting zone, and relative specific power and specific annual consumption of the irradiation systems for plants in industrial greenhouses.

5. CONCLUSION

The standards and measurement techniques developed at VNISI in 2016–2017 set the following:

– Required characteristics of LED luminaires for greenhouses, including the efficiency require-

[2] Quantum sensor "*LI-190R*" is an integral means of measurement corrected in the wavelength range of (400÷700) nm and available on the Russian measuring instruments market.

ments of luminaires in PAR region (which have been formulated for the first time in global practice) expressed as photon values (GOST R57671–2017 [4]);

– Methods for measuring the parameters of irradiation of plants in greenhouses: horizontal photosynthetic irradiance, average horizontal photosynthetic irradiance and its uniformity in the installations for irradiating plants from above, and a vertical photosynthetic irradiance in multi-story rack-type installations (the preliminary standard 211–2017 [5]);

– The combination and sequence of specifically described steps which provide the measurements of photosynthetic photon flux of luminaires carried out with goniometer "*RIGO 801*" and spectroradiometer "*CAS140*" (FR.1.37.2017.27374 [14];

– The combination and sequence of specifically described steps which provide the measurements of illuminance and photosynthetic irradiance of plants in greenhouses carried out with the luxmeter "TKA-LUX" (FR.1.37.2017.2736 [15];

– The combination and sequence of specifically described steps which provide the measurements of photosynthetic irradiance of plants in greenhouses carried out with the quantum sensor "*LI-190R*" (FR.1.37.2017.27375 [16]);

– The combination and sequence of specifically described steps which provide the measurements of spatial distribution of luminous intensity of luminaires and relative spectral distribution of radiation, as well as the calculation of relative specific power and specific annual consumption of the systems for irradiation of plants in industrial greenhouses (FR.1.37.2017.27373 [17]).

The standards and methods described in this paper are just the first step along the way towards creating a comprehensive regulatory foundation for the illumination/irradiation of plants in industrial greenhouses and other "sites with covered ground". To make those foundation deep and broad, long and expensive studies must be conducted, exploring the influence of intensity and spectral composition of radiation on the productivity of greenhouse crops. VNISI in cooperation with well-known industrial agriculture enterprises, like the Institute of Bio-Physics (RAS) and the Timiryazev Agricultural Academy in Moscow, had already conducted such research, pursues it further and will continue in this direction [9, 10, 18, 19], with no intention to stop.

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UV DISINFECTION TECHNOLOGIES FOR WATER, AIR AND SURFACE TREATMENT

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ABSTRACT

A review of the main modern achievements is presented in development, production and application of UV bactericidal lamps and irradiating installations with their use to disinfect water, air and surfaces. It is shown that LIT NPO takes a worthy place among most large-scale global manufacturers of such lamps and installations.

Keywords: UV radiation, UV irradiation, mercury lamp, amalgam lamp, UV radiating diode, UV installation, UV station, LIT NPO

The history of artificial UV radiation using comprises more than 100 years. For example, the fact that UV radiation disinfects water and air was known and began to be used at the end of the XIX and at the beginning of the XX centuries. However, understanding the fact that UV radiation is a unique tool to initiate or carrying out many physical and chemical processes on the surface and inside different environments only appeared within the seventies – nineties. It was time when, on the one hand, the range of tasks in chemistry, biology, medicine, material science, ecology, etc., where chemical methods were either powerless or expensive, or not eco-friendly, became obvious, and on the other hand, nature of many chemical, physical and biological processes became clear at the atomic and molecular level.

At present, technologies based on UV irradiation dynamically develop in industry, medicine, municipal services, power engineering, agriculture, etc. due to serious investments into developments and industrial production of modern powerful high-effective UV radiation sources and irradiating devices based on them. This in its turn is caused by these technologies application scope increase in the above-named fields [1].

The problem of disinfecting natural and sewage water became a development drive of UV irradiation use during the last 25 years. Its scope exactly motivated the leading world institutes and lighting companies to raise quality level of UV radiation sources development and production. New types of these sources were created, which provided new abilities of UV radiation in other fields as well.

A need of industrial water disinfection by non-chemical methods arose at the turn of the eightieth – ninetieth of the last century, when chlorine and its derivatives total harm for people and nature during the traditional chlorination of natural and sewage water was revealed. Strict standard limitations of chlorine derivatives concentration in water on the one hand, and general hygienic requirements, including microbiology (viruses, etc.), which significantly increased in the ninetieth, on the other hand, forced to change both general technological approaches to cleaning natural and sewage water, and approaches to the disinfection [2–5].

Municipal services and industries began to test and accustom ozonization, micro-, ultra- and nano-filtration commercially. UV treatment, replacement of liquid chlorine with more safe chlorine agents and combinations of these technologies pro-

Fig. 1. UV disinfection system of the Northern waterwork (St. Petersburg) of 1,584,000 m^3/day productivity (number of lamps type ДБ 350 is 3888 with total power consumption equal to 1.36 MW)

Fig. 2. UV disinfection station of surface water (Budapest, Hungary); number of lamps type ДБ 350 is 600, total power consumption is 210 kW

Fig. 3. UV disinfection station of the Kuryanovsky treatment facilities (Moscow)*;* number of lamps type ДБ 600 is 6120, total power consumption is 3.7 MW

Fig. 4. UV disinfection station of waste water (Beijing); number of lamps type ДБ900НО is 864, total power consumption is 700 kW

vide an improvement of water purification quality, its sanitary and ecological safety [6].

For the last years, this experience and practice exactly turned UV irradiation from the technology of little expenditures and special application conditions into economically effective basic technology of deep water disinfection, which is widely applied both: independently, and in a combination with other above-named technologies. For this purpose, it was needed to develop and master manufacture of large-scale industrial installations based on powerful UV radiation sources, to create stations of preparing drinking and sewage water treatment of any productivity.

Examples of the correspondent solutions are waterworks of St. Petersburg, Nizhny Novgorod, Budapest, New York and many other cities. In 2003–2008, Vodokanal SUE of St. Petersburg implemented a comprehensive upgrade of the water disinfection system. A modernisation result became creation of the world's largest system of UV stations, which encloses water supply of St. Petersburg and its suburbs [7]. Fig.1[1] shows one of nine UV systems for preparation of drinking water in St. Petersburg: the Northern waterwork (the largest one in Europe).

The largest in the EU project of UV disinfection station in a system of drinking water preparation is implemented in Budapest (Hungary). Productivity of the station is 600 thousands m^3/day, Fig. 2 [8].

Within the industrially developed world, a total transition from chlorination of sewage water to UV disinfection takes place. So in the USA, more than 65 % of sewage water scope is already treated by

[1] The UV lamps and/or the comprehensive irradiating equipment with the lamps presented in this and in all subsequent figures are developed, made, supplied and put in commission by LIT NPO.

Fig. 5. UV irradiation of inner surfaces and air of underground carriages in depot

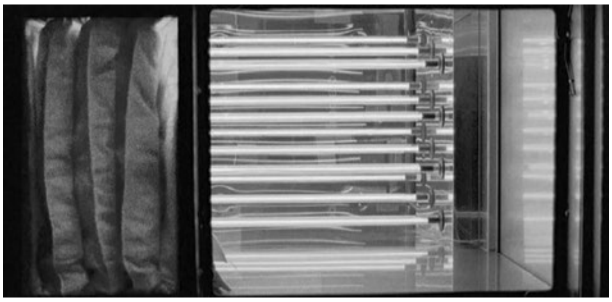

Fig. 6. UV module, which built in ventilation system of up to 15000 m^3/h productivity

UV irradiation, and in Russia it is approximately 30 %.

The world's largest UV system of sewage water disinfection consisting of four UV stations disinfects all municipal sewage water of Moscow with the design productivity of $3 \cdot 10^6$ m^3/day, Fig. 3.

As well intensely, technology of sewage water UV disinfection is introduced in the advanced countries of Asia (Republic of Korea, Malaysia, People's Republic of China). Fig. 4 shows an UV station of 780,000 m^3/day productivity started in Beijing in 2016 [9].

During recent years, one can observe a similar dynamics of UV radiation use for air disinfecting and cleaning, but several years later than water [10–13]. People in the urbanised world, more often are in a closed room: at home, at work, at school, in a high education institution, in transport and even on vacation.

And if earlier buildings and constructions were designed taking into account external air quality with a considerable part of natural ventilation, then now to achieve a comfortable state, air heating and conditioning are widely applied, including a partial recirculation for energy saving. And this requires an essentially new quality of air environment.

Global migrations of population all over the planet, with their concentration in urbanised space, with a long time of people stay in places of mass gathering cardinally aggravated the situation of broadening infectious diseases, which are transferred in airborne way. Flu epidemics within the last thirty years are no more local territorial phenomena.

Earlier, a priority was always given to chemical factors of air environment quality. Now, taking into account the above stated, microbiological factors play an increasing role. Safety of air environment not only by chemical but also by microbiological factors forced to solve problems of economic and effective disinfection of large air volumes separately or within general systems of their cleaning, conditioning, etc.

Therefore from medicine and food industry with traditionally high special requirements for microbiology of air environment, UV disinfection technologies expand to systems of air cleaning of general purpose and to transport. As well as in the water disinfection, more general new tasks caused a necessity to develop these systems. For recent years, a range of irradiating devices for air and surface disinfection was created in Russia. These devices are in particular used for emergency treatment of operating rooms and of other rooms in hospitals, in ventilation systems, as well as at food productions, offices, schools, warehouses and transport, Figs. 5, 6.

Photosynthesis, photocatalysis and photopolymerisation on surfaces, in liquids and gases using UV radiation of different spectral intervals are applied in microelectronics, chemical, pharmaceutic, printing and other industries. And processes of the so-called activated photo-oxidation are widely used to clean gases and liquids out of micro impurities [1, 14].

Studies of photobiological effect of UV radiation are significantly extended (for example, to stimulate growth and increase stress resistance of plants (Fig. 7), and this is not the full list of up to date use of UV radiation as a high-precision influence tool on processes and environments.

The success of UV disinfection technologies, and first of all, of water disinfection, would be impossible without a significant progress of UV radiation sources. For the last twenty years, UV radiation discharge sources in particular showed a huge scientific and technological increase in their development. Such sources of UV radiation as semiconductor UV radiating diodes quickly develop. As it was noticed earlier, the main stimulus of the specified technologies development is the problem of en-

Fig. 7. Platform with UV lamps hung on tractors

vironment disinfection, and the main characteristics of the relevant UV radiation sources and ballast for them are as follows:

- Bactericidal flux;
- Bactericidal efficacy;
- Lifetime of the source;
- Decrease of bactericidal flux by the end of the source lifetime;
- Lifetime, compactness and cost of the ballast;
- Safety, environmental friendliness and adaptability of the source application.

And in our opinion, as UV radiation sources, UV discharge lamps only and in some prospect, semiconductor UV radiators can be used.

As to the latter, we know the following:

- Semiconductor UV radiation diodes of the near UV range are developing now rapidly [15, 16]. At the market, diodes have appeared with wavelengths of (360–395) nm, which supersede, for example, traditional UV MHLs in particular at the market of UV radiation sources for photo hardening of coatings.
- In the semiconductor diodes of UV–C interval, an active study of their application in the systems of disinfecting water, air and surfaces takes place at least in special applications [17, 18]. The first commercially available diodes and devices based on them are appeared, which radiate in a (255–270) nm range [19]. At present, works have been published, which is showing a great success in development of UV–C diodes in (268–278) nm range (in particular, their energy efficiency is declared to be of 5 % and more) [20]. However, semiconductor UV–C radiators come along more slowly than normal light emitting diodes, what is connected with some unresolved physical and technological problems [15].

So, the leader in the UV–C diodes field *Crystal IS* Company (USA) proposes in particular Optan diode of UVC LED8–250–280 type with maximum radiant flux of 10 mW in spectral interval of (250–280) nm with power consumption of 3.6 W. Energy efficiency of the diode is of about 0.28 %. Such low energy efficiency is caused by a variety of reasons, basic of which are non-radiative recombination of charges on the dislocations out of the active layer, discrepancy of the semiconductor lattice and of the substrate constants, stacking faults, and increased ohmic resistance of the *p*-*n*-junction.

A serious problem of UV light emitting diode development is to obtain high-doped *AlGaN* layers of *n*- and *p*-types with a high concentration of *AlN* and to provide a rather low operation voltage and the low power consumption. One way of this problem solution is use of super lattices and forming an intermediate layer between the substrate and semiconductor to coordinate the lattice constants. This direction work is in progress [21], and the leading manufacturers prepare standardisation of measurement methods of UV–C diode electric and radiometric characteristics under the aegis of the International Ultra-violet Association (IUVA)) [22].

Lifetime of modern UV–C diodes with wavelength of (255–265) nm for example, is rather low as well: of about 1000 h when radiation flux decay to 50 %. Nevertheless, such radiators are already applied, particularly in water transmission measurement devices (τ metres) and in express biotesting devices (devices for bactericidal sensitivity curve measurement (BSCM) [19].

The main UV radiation sources of broad application are discharge UV lamps. They allow obtaining big specific energy-effective radiation fluxes, have rather long lifetime and are rather easy-to-work. Depending on the discharge conditions and on the filling composition of these lamps, they can have continuous and/or linear radiation spectra. Mercury, metal-halogen, hydrogen, excimer and other discharge UV lamps are now manufactured for different applications. Their envelopes are made of rather transparent for UV radiation glasses, most often these are quartz and uviol glasses. By power supply methods, the lamps can be divided into electrode and electrodeless, with continuous and pulse operation modes [1, 23].

At present, electric discharge in mercury vapour with inert gas mixtures is the main source of bactericidal UV radiation [1, 23]. The lamps with such

Fig. 8. Production of amalgam lamps

discharge are divided into LP mercury lamps, amalgam lamps (LP) and HP mercury lamps (according to the domestic classification, which corresponds to the middle pressure discharge lamp term used abroad).

The main comparative operational characteristics of these lamps are given in the Table.

The main advantage of the sources based on the mercury LP discharge is high energy efficiency in the bactericidal spectrum interval, which with optimum discharge parameters of modern powerful lamps is about (35–40)% [24].

HP lamps have a typical band (striped) spectrum corresponding to a considerably smaller efficiency.

As to the amalgam lamps, though they are mercury-containing but are much safer ecologically.

At present, global manufacturers of LP amalgam lamps of *Philips* (Netherlands), *LightTech/LSI* (Hungary/the USA), Heraeus Noblelight (Germany), LIT NPO (Russia/Germany), etc. offer lamps of 50 to 1000 W power. Their energy efficiency in the bactericidal interval is from 30 to 40 % and useful lifetime is up to 16000 h. In Russia, the leader in the development and manufacture of powerful amalgam lamps is LIT NPO, which has two lamp productions: the first one being the main is in Moscow and operates since 1996, and the second was established in Germany in 2010, Fig. 8. LIT Company manufactures a wide range of UV lamps for water and air disinfection. The most powerful of them is ДБ1000 lamp of 1000 w power. In 2014 production of ozone-generating lamps with radiation in the mercury line of 185 nm is begun for special applications.

Based on these UV LP lamps, installations for water disinfection with unit-productivity from 0.5 to 10,000 m^3/h are produced. Most large-scale manufacturers of them are as follows: *Trojan* (Canada), LIT NPO (Russia/Germany), *Wedeco Xylem* (Germany/ USA), *Halma group* (*Hanovia*, *Aquionics*, *Berson*) (Great Britain/ USA/Netherlands), *Calgon Carbon* (USA) and *NewLand* (PRC).

Traditionally UV HP lamps of (0.1–20) kW are made in *Philips* (Netherlands), *LightTech/LSI* (Hungary/ USA) and *Heraeus Noblelight* (Germany). The leaders of UV installation production using these lamps are *Trojan* (Canada), *Atlantium* (Israel) and *Berson* (Netherlands).

One can notice also other discharge sources of UV radiation, which for a range of reasons were not wide common, for example, xenon pulse and excimer lamps.

The first ones are only used for special disinfection tasks but even there they are applied to a limited extent because of a short lifetime (100–1000) h relative to a low bactericidal efficiency (8–10)% and due to high prices of the lamp-ballast set [25]. Excimer lamps radiate due to disintegration of special molecules being an excited atom system. These molecules can include different atoms (for example XeF^*) or identical (for example, Ar_2^*). Excimer lamp radiation is narrow-band, and maxima of radiation bands depending on the used molecules are within wave length interval of (120–360) nm. Energy efficiency of these lamp discharge depends on the power and can reach 25 % at a low power (of about (10–20) W). Energy efficiency of excimer lamps in the UV spectrum interval is almost twice lower than of UV LP mercury lamps, and with power increase it noticeably decreases. Application of such sources for commercial disinfection is restraining because of low bactericidal efficiency, high cost and complexity of the ballast. In our country, the leader of development and production of such excimer lamps is the Institute of High-Current Electronics of the Siberian Branch of the Russian Academy of Science (Tomsk). And in 2006–2009, a commercially available device for water disinfection *(Instant Trust*) was developed by *Philips Lighting* Company.

Table. Main operational characteristics of UV lamps based on mercury discharge

Parameter	HP lamps	Traditional LP lamps	Amalgam LP lamps
Lamp power, W	2000–20000	15–100	100–1000
Energy efficiency of lamps in the bactericidal interval,%	≈ 10–12	≈ 35–40	≈ 35–40
Lifetime of lamps, h	4000–8000	12000–16000	12000–16000
Formation of by-products in water	possible	impossible	

CONCLUSION

A high efficiency of UV irradiation makes it an irreplaceable element of the modern drinking water preparation system. Introduction of UV irradiating equipment for disinfection of sewage water allows eliminating chlorination at operating treatment facilities, which is potentially dangerous for population and environment. Systems of air and surface disinfection will be inevitably used as well as UV water treatment systems. Their development will require more time and efforts first of all concerning creation of a necessary regulatory basis and introduction of UV irradiation technology itself into medicine, food industry and transport.

The core of any type UV installations is a source of UV radiation. UV LP amalgam lamps have the greatest expansion and development, and their progress for the last twenty years is obvious. The leading world companies produce such lamps of (800–1000) W. Semiconductor sources of bactericidal radiation are also rapidly developed. LIT Company, as well as other UV installation manufacturers, observes with interest and recognises progress in development of such sources, however, do not consider them for the present being competitive with the traditional discharge UV lamps.

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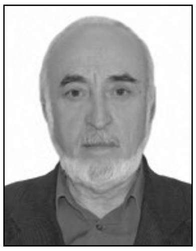

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POSSIBLE USES OF EQUIPMENT IN SPACE TO CONTROL EARTH SURFACE ILLUMINATION

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ABSTRACT

The article reviews research and development from Russian and beyond into the use of equipment in space to control illumination of the earth surface. The main engineering challenges associated with structural selection, opening and completion of space reflectors and screens are described. Preliminary estimates of what constitutes an excessive level of illumination, impacting humans and other living organisms are given. Some technological and economic issues associated with the creation of the control systems for the illumination of the earth's surface are presented. A need of additional studies of conditions for people living in the illuminated regions is substantiated.

Keywords: the Sun, orbital illumination, reflector, screen, solar-and-sailing ship, light pollution, ecology

1. INTRODUCTION

Significant consumption of hydrocarbon fuel for electricity generation to power external illumination during the night time (NT) and associated changes in the climate are among the main global environmental challenges.

Both these challenges can be addressed using space equipment to change the illuminance of earth's surface. Reflectors and opaque screens can be placed in the Earth's orbit and at libration points[1] of the Earth – Sun and Earth – Moon systems. This proposed technology assumes that some rare engineering problems can be resolved. For instance, there is currently no comprehensive and versatile evaluation of the potential consequences of a change in the light situation. The purpose of this article is to analyse engineering challenges associated with using space equipment to control illumination of earth's surface and likely indirect consequences for ecology and vital human functions.

2. REVIEW OF PROJECTS TO CONTROL ILLUMINATION OF THE EARTH'S SURFACE FROM SPACE

The Sun's light can be used for external illumination at night in some regions. The light can be directed using systems of space vehicles (SV) with reflectors located in an Earth orbit, Fig. 1. The use of such space reflectors was proposed at the beginning of the 20th century by astronautic pioneers Yu.V. Kondratyuk and G. Obert.

Orbital illumination can be especially important for transpolar regions, which experience the polar night phenomenon, as well as in areas where natural disasters and emergencies have occurred.

In the late 1960s, an orbital illumination system project intended for military and civil applications was published in the USA [1].

These proposals were further developed in the 1970s within the Space Light programme proposed

[1] In libration points (Lagrange points), a third body, which is only affected by gravitation forces from two other massive bodies can remain fixed relative to these two bodies

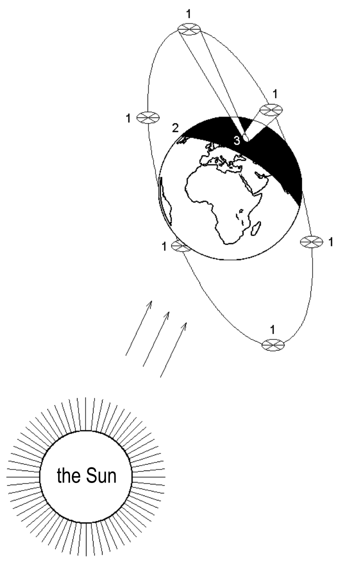

Fig. 1. A system of orbital illumination: ***1*** **–** space reflectors; ***2*** **–** terminator (light partition line); ***3*** **–** illuminated region

by K.A. Ehricke [2], which envisioned placing several systems of space reflectors in Earth's orbit. Taking into account these and other similar projects, a system of orbital illumination for the territory of the USA and adjacent states (densely populated industrial regions, Alaska, and Panama Channel) was developed using reflectors which would total 780,000 m^2 in area (NASA research centre, Langley) [3].

Since the late 1980s, the problem of global climate change has become more and more apparent. In order to slow the greenhouse effect, a method to reduce the solar radiation flow reaching the earth's surface by 2 % by using a screen 2000 km in diameter placed at the Earth – Sun system libration point *L1* has been put forward, Fig. 2 [4].

In research from Russia in 1992 [5], a similar structure is described with a variable transparency. The system consisted of modules, which can adjust screen plane inclination relative to the direction of solar radiation.

Instead of a monolithic screen, 800,000 autonomous small SV screens can be also used to lower solar radiation by 1.8 %, with a general weight of $2.0 \cdot 10^7$ t (the USA, 2006) [6]. The main problem associated with this system is the control of such a large number of objects and their subsequent utilisation.

In Russia, a large programme of work was undertaken to create space equipment for the control earth's surface illumination.

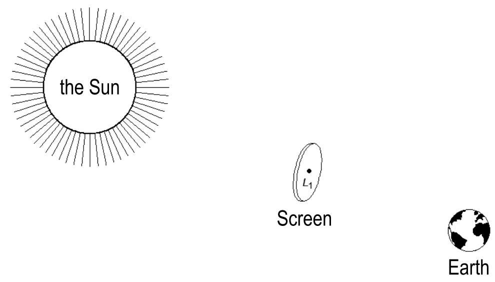

Fig. 2. A screen in the Earth-Sun system libration point used to reduce insolation of the earth surface

In 1992–1993, a system of 100 space reflectors (called SV reflectors) totalling 30,000 m^2 in area was developed together with the Research centre of M.V. Keldysh for orbital illumination of subpolar cities located at a geographic latitude of 70 ± 2° in the Northern hemisphere (Murmansk, Norilsk) [7, 8].

In 1994, the Znamya-2 (Banner-2) experiment was conducted, which opened out a film reflector with aluminium coating under space flight conditions [9].

In 2009–2013, proposals were published to create a space system to adjust the temperature condition of the earth's atmosphere intended to address power and climate issues [10, 11]. The basis of this system is a solar-sailing ship (SSS) located at the libration points of photo gravitation field[2] of Earth-Sun or Earth-Moon systems. SSSs allow reducing or increasing atmospheric temperature by changing the illumination of the earth's surface by the sun. Aluminium foil is used in their production, which would be manufactured using resources from the moon.

At present, there is no industrial experience of producing space equipment at the described scale and size for the proposed structures. Therefore, a number of critical technological issues need to be resolved to enable their creation.

3. THE MAIN ENGINEERING CHALLENGES ASSOCIATED WITH THE DEVELOPMENT OF LARGE-SCALE SPACE REFLECTORS AND SCREENS

The main structural requirements for an SV reflector structure is a stabile geometry and the ab-

[2] In a photo gravitation field, the influence of gravitation forces and of sunlight pressure is accounted for.

sence of any folds or overlaps. It is also important to decrease the mass and design an effective and reliable opening mechanism for the reflector under space flight conditions.

One of the most encouraging designs uses a frameless structure for the reflectors formed by centrifugal forces. However, although their mass is low, at present, frameless structures do not provide the required accuracy of surface configuration, which is required for maintenance, are influenced by the Coriolis force during reorientation and require damping of oscillations from gyroscopic forces [8].

Vibrations the SV reflector can cause reflector oscillations, which in turn can displace the light beam relative to the illuminated region (a deviation of 2′ corresponds to a light spot shift of 1 km). Therefore, SV reflectors require exact stabilisation.

The SV reflector's turn can be controlled relative to its own centre of gravity due to gyroscopic effect. Therefore, project [7] selected a rope ring flywheel design, which allowed reducing the mass of the construction.

However, the problems connected with active damping of nutation oscillations of the rotating sail and of the rope flywheel, as studied in [12], are not yet resolved. Therefore, only an original design gyro flywheel can be used in practice.

To keep SV reflector operational under space flight conditions, it was suggested that the metal coating cold be deposited by means a correspondent unit and with a reserve of the deposited material onboard [7]. But for now the technology for automatic metal coating deposition onboard is not yet available. Therefore, there is a need for further study of keeping SV reflectors optical properties during their long ground storage in the context of space technology already available today.

Safe keeping of the film and of the reflector coating under the influence of external conditions during space flight is a significant unknown, which can be only checked by long flight tests.

SSSs will be the most large-scale space construction in the history of humanity: the screen's diameter will be of (1500–1960) km, and its mass will be of about $5.6 \cdot 10^7$ t [10, 11]. Therefore, besides the described challenges of creating SV reflectors, there is a need to develop control methods for a structure of such mass and dimension.

To incorporate the impacts of a working SSS structure in lighting calculations, all factors influencing the final result should be accounted for. The influence of a darkening effect of the Sun disc edge on decreasing its radiation flow by means of SSSs has been studied, and it has been shown that to reduce the solar constant by 0.50 %, an SSS of 1500 km (instead of 1690 km) in diameter placed at the centre of the Sun disc is sufficient [13].

Compared to studies of the technological aspect of developing space screens and reflectors, research into the potential indirect impacts of a changing light situation on global ecology and its vital functions for humans is less developed.

4. A PRELIMINARY EXPLORATION OF ECOLOGICAL IMPACTS OF EARTH SURFACE ILLUMINATION CHANGE

Evaluating the ecological impact of excessive illumination created by SV reflectors and SSS is closely related to the study of light pollution created by artificial light sources in cities and industrial areas.

It follows from the study of light pollution [14–17] that the use of artificial illumination during the night time can violate photobiological reactions of different living organisms, including people.

In studies [14.18.19], it is recommended that radiation sources with a high concentration of blue light portion (0.44–0.48) µ are applied with care at night.

Some organisms use celestial bodies to orient in space [20, 21]. At present, this biological mechanism is insufficiently researched. Therefore, it is difficult to estimate the influence upon it of changing external illumination.

A weak UV radiation in the UV-B interval (0.28–0.32) µ is critical for many organisms. Annual cycles of this radiation in the mid and high latitudes can be considered to activate season migrations and sleep of some animals [22].

One more important aspect of the potentially changing the natural light situation it the light polarisation of celestial bodies in the atmosphere. Light pollution is created by unpolarised radiation of land-based light sources, which additionally complicates orientation of some live organisms [23]. Thus, illumination using SV reflectors would be closer to natural.

In study [24], characteristics of the reflectors and safety of orbital illumination system SV reflector operation were analysed. Reflectors with alumini-

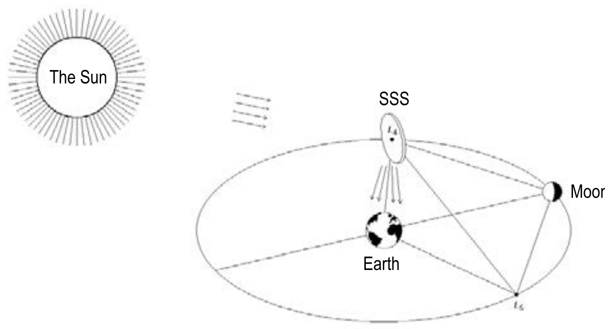

Fig. 3. Placing an SSS in the Earth-Moon system ***L4*** libration point

um, silver, titanium, gold and copper coatings were considered.

A calculation of the correlated colour temperature showed that optimal visual perception by an operator at night is achieved with gold or copper reflector coatings.

In article [25], an analysis of spectral characteristics of reflected solar radiation for the five reflector coatings mentioned above is performed. To decrease reflected UV-B radiation level, reflectors with silver coating are suitable, and to decrease both it and the light blue portion level (0.44–0.48) μ, reflectors with copper or gold coatings can be used.

Spectral characteristics of the Sun's reflected radiation for different metal coatings of SV reflectors are given in Table 1.

Evaluation results [24, 25] suggest that the load on visual organs of an operator and undesirable ecological exposure can be reduced by using different metal reflector coatings depending on the local time of day in the illuminated region of the earth's surface.

An important operational safety concern for orbital illumination systems is the constant control of the earth surface illumination level. Therefore, there is a need for the possibility to quickly turn off the reflectors from the earth surface's to recover natural illuminance level.

By their level of environmental impact, SSSs considerably surpass orbital illumination systems. Operating one of the proposed SSS designs assumes a decrease of earth surface illuminance by 0.5 % [10.11], which is enough to control atmospheric temperature mode. To ensure safety, the possibility of quickly return to natural levels of illumination needs to be envisioned.

The structure with weakening adjustment proposed in [5] is complex because of a large number of moving parts and final control elements. Therefore more likely, a reliable and quick recovery of natural illumination is only feasible by an emergency dismantling of the SSS structure.

There is no unity of opinion concerning trends and reasons of earth climate in the scientific community, as well as concerning anthropogenic contribution to this process. Besides the widely known and discussed hypothesis of global warming, there is a counterhypothesis of global cooling. Quantitative evaluations of the contribution of each factors determining earth climate are approximate [26].

So any artificial exposure on the climate should lead to its unpredictable and irreversible changes.

For this reason, the SSS design for strengthening illumination of the earth surface was examined in detail [11].

It has a two-way reflecting surface 1960 km in diameter and is placed in libration points *L4 or L5* of the Earth-Moon system, Fig. 3.

Table 1. Characteristics of the Sun's reflected radiation for different metal coatings

	Metal coating				
	aluminium	**silver**	**titanium**	**copper**	**gold**
Correlated colour temperature, *K*	5200	5180	5130	3655	3650
Total illuminance in spectral interval of (0.36–0.83) μ, lx*	7.2	7.6	4.7	5.2	6.1
Irradiance in spectral interval of (0.28–0.38) μ, mW/m^2*	1.8	1.4	1.1	0.7	0.7
Irradiance in spectral interval of (0.44–0.48) μ, mW/m^2*	4.3	4.4	2.7	2.1	2.0

* Under clear atmosphere conditions

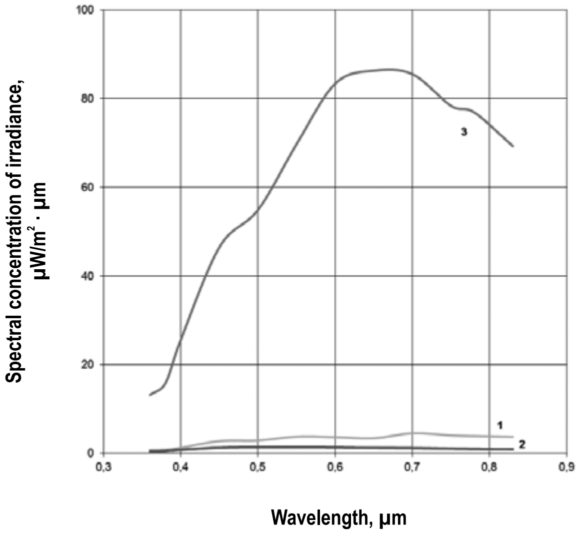

Fig. 4. Radiation spectra for the full Moon (1), SSS (diffuse component) (2) and for a SV reflector with reflector copper coating (3)

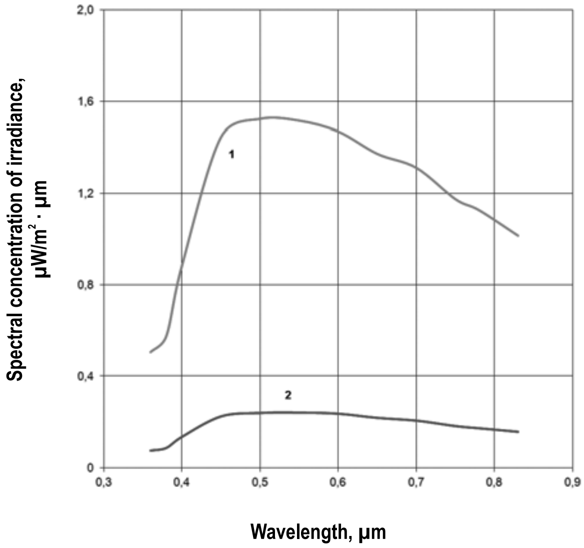

Fig. 5. Radiation spectra for the Sun (1) and SSS (a specular component) (2)

An evaluation of earth surface irradiance from this SSS [27] shows that:

1. The reflected UV radiation is not a direct risk for people, and special measures to protect against it are not required.

2. The irradiance in the UV and in the visible spectrum intervals is excessive during the night time (as it exceeds natural illumination by 5–8 orders of magnitude in the case of specular reflexion). As to the radiance, the SSS observed from Earth, will be comparable with the Sun and the Moon.

3. The spectrum of the reflected radiation can create discomfort for the operator's work during night time.

The calculation results for the illuminance from an SSS are given in Table 2.

Fig. 4 allows to estimate the spectra of visible radiation for full Moon, SV reflector with copper coating and SSS (diffuse component) under clear atmosphere conditions, and in Fig. 5 visible radiation spectra for the Sun and SSS (specular component) under the same conditions are presented.

When opening orbital illumination and SSS systems, the influence of illumination change on ozone formation processes in the atmosphere and related weather changes should be also investigated [13].

A final assessment of light exposure modes can be only made from the results of real tests.

It should also be stated that in order to understand negative impacts on nature and people, long term exposure is required, just as it has occured with light pollution in big cities and industrial areas.

Thus, space experiments of short-term irradiation of the earth's surface by low-power flows of reflected radiation of the Sun are not dangerous for people and nature.

After the safety boundaries for earth's surface illumination change are determined, an engineering and economic analysis of developing the space equipment for these projects should be carried out.

5. ENGINEERING AND ECONOMIC ASPECTS OF DEVELOPING ORBITAL ILLUMINATION SYSTEMS AND SSS

In the near future, developing orbital illumination systems will be associated with the operation of new super-heavy carrier rockets capable of placing several SV reflectors into orbit from one start.

The results of research (2013) performed at the University of Pennsylvania show that the development of orbital illumination systems will be economically practical once the cost of placing objects into orbit drops to within several hundred dollars per kilo of payload [28].

To produce the reflectors, there are two types of polymeric films currently manufactured which are most suitable by their physical and mechanic characteristics, as well as their production availability: polyethyleneterephthalate (PETF, mylar) and polyimide (PM-1EU, kapton) [7, 8, 28].

Table 2. Illuminance and irradiance from the SSS of a reflector 1960 km in diameter located at libration points of *L4 or L5* of the Earth-Moon system (under clear atmosphere conditions)

Factor	Value
Correlated colour temperature, *K*	5200
Total illuminance in a spectral interval of (0.36–0.83) μ, lx: specular component diffuse component	 $1.7 \cdot 10^4$ 0.1
Irradiance in a spectral interval of (0.28–0.38) μ, W/m^2*	4.2
Irradiance in a spectral interval of (0.44–0.48) μ, W/m^2*	10.1

* Specular component

Aluminium, titanium and copper are widely used in space equipment production. Therefore, it will not be difficult to use these materials in manufacturing SV reflectors. The high cost of gold and silver coatings could be a limitation to production, but according to a proposed concept [24, 25], reflectors of different material types should be used together in orbital illumination systems. Therefore, gold and silver coatings would only need to be applied to a part of the reflectors.

Developing orbital illumination systems will lead to changes of living and working conditions for a large number of people. So, besides ecological impacts, social, psychological and medical aspects of the design should be also studied carefully.

An evaluation of the influence of illumination change on the daily life of people, on their work and rest modes, on domestic and industrial room structure and on the length of time spent outdoors is necessary. As there is a connection between some social phenomena and the length of the light day and Moon phases, theoretical a possible influences of changes in illuminance on behaviour of different social groups, on number of law offences, frequency of mental illmess, etc. among the population of the illuminated regions should be investigated.

An in-depth study of the influence of external illumination on the photobiological reactions of different living organisms could suggests that there are wide opportunities for intentional exposure for the benefit of the economic activity of people. Fundamentals of developing a technology of light ecosystem control are formed, as well as of creating favourable conditions for the life and work of people.

This technology could increase the efficiency of marine and land organisms, control their migration, create unfavourable conditions for harmful and dangerous organisms in the illuminated areas. At the same time, a light situation can be created which would increase work efficiency, improve life, prevent diseases and mental disorders.

Article [2] describes a system of orbital illumination, which could control climate and increase agricultural efficiency over large areas of the earth's surface (so-called Biosoletta). The system of orbital illumination currently under consideration [7, 8] covers a circular region 15–17 km in diameter, which ensures greater ecological safety in comparison with the Biosoletta.

Within a limited region, different light exposures can be applied to living organisms, without the risk of global ecological consequences.

Light channels of exposure on the ecosystem have the following advantages compared with other instruments (chemical, radiation, etc.): zero lag control, universality, comparatively low risk (negative impacts only arise in cases of long exposure).

As to the SSSs, it should be noted that to operate them in the libration points of Earth – Moon or Earth – Sun systems, the development of the Moon would need to be advanced: building there a permanent base with the associated infrastructure and creating an assembly production in circumlunar space. In such case, the power should be enough to produce SSS structure elements of opaque glass [4] or aluminium foil [10, 11] obtained on the moon surface.

Construction of SSSs made of nickel iron from asteroids resources [5] is a more complex challenge for the present.

From the engineering point of view, a detailed study of the structural solutions used in the SSSs and of the methods of their opening at orbit is necessary.

A final question is the decommissioning of space equipment, which has exhausted its life time.

Termination of SV reflectors and SSS operation

It has been proposed to take end of life SV reflectors of the orbital illumination system [7, 8] to a higher orbit for burial by means of partly keeping solar sail properties of a reflector.

Concerning SSSs, it should be stated that the problem of decommissioning large-scale space structures placed higher than a low Earth orbit has no practicable solution at present.

The big mass of an SSS creates risks of control loss for such a huge structure. Thus, a constant or periodic presence of the crew on-board to control and maintenance the working capacity is required.

Upon completion of its life time, it was planned to return the SSS to the assembly production [10], however, big mass reserves make it possible to have material resources necessary for its periodic repair, and a gradual mass consumption can be compensated by a gradual delivery of the "ballast" using different space transport systems. This suggests that in principle such structures have a long life time.

From the point of view of operation safety, an SSS structure made up of separate sections is preferable. Taking into account the big mass of the SSS, safety measures can include technological solutions, which enable the quick dismantle and dissolution of the structure's elements (for example, using pyrotechnic technologies).

For a the quick decommissioning of reflectors with a large area, one technique of interest is that initially proposed for the burial of radioactive waste in space [29]. These proposals were developed further within a concept of an SV engine system using the recovered material (space debris) as a fuel [30]. Use of this technology allows de-escalating the reflector and simultaneously controlling the SSS movement (for example, to direct its trajectory to the assembly production).

CONCLUSION

The presented review describes the current international level of space equipment development for earth surface illumination control. Evaluations of excessive illumination and its influence on people and other living organisms are presented, an engineering and economic aspect of development of earth surface illumination control systems is described, and a need of further studies of possible indirect consequences of a change in the light situation change is substantiated.

Further studies should determine the practicability of orbital illumination and adjustment of earth surface insolation use by means of SSSs taking into account the risks of climate change and their possible consequences.

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PHOTOMETRY OF LIGHTING DEVICES: CURRENT STATE AND PROSPECTS FOR DEVELOPMENT

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ABSTRACT

The article is a dedicated review of recommendations, methods, and tools for establishing and communicating the standard measurements of photometric, energy, and photon value units. The article considers how photometric values units are reproduced and traced through to the basic units of the International System of Units (SI), as well as how methods and tools of transposing standard measures from primary standards to measuring devices in test centres and laboratories. Modern day measurement requirements for test methods and facilities for illumination devices used in different illumination systems are also considered.

Keywords: optical radiometry, photometry, colorimetry, spectroradiometric approach, detector based approach, photon quantity, goniophotometry, image photometer

1. INTRODUCTION

Recent decades have seen a significant leap forward in the development of light sources [1,2], radiation receivers [3,4], measurement methods and precision instrument design as a whole [5–7].

This process develops alongside the introduction of quantum technology into metrology [8], which arises from the understanding of the wave nature of light, and stems from the definition of the candela as a base unit of luminous intensity in 1979.

International choice in favour of quantum technology or photonics requires improving measurement tracing and reliability for both single photon and multiphoton processes. The latter requirement remains in the research and development stage, but the evolution in the candela reproduction method is in the direction of the quantum approach (for example, candela is the luminous intensity of a monochrome radiation source in a certain direction with 540x1012 Hz frequency, radiant intensity of 1/683 W/sr and photon radiant intensity equal to $(683 \times 540 \times 10^{12} \times 6.626068\,96 \times 10^{-34})^{-1}$ photon/s·sr.). The shift is timely, considering that four units of the SI system (kg, mol, Kelvin and Ampere) have been redefined in physical constant terms in order to create a universal quantum SI system based on fundamental constants [9,10,11].

Document [12] prepared and officially approved by the Consultative Committee for Photometry and Radiometry (CCPR) of the International Committee for Weights and Measures (CIPM) is a memorandum for the practical use of the candela definition, which updates and expands the preceding version of this document that was limited by it approach to the candela based on the 1979 definition, which is still applied. Photometry and measurement units used in optical radiometry are closely connected by the candela definition as the base unit of the SI. The memorandum covers the implementation of the candela, as well as other units of measuring radiometric and photometric standard values. Recent progress in the generation and application of separate photons provide many possibilities in evaluating radiation fluxes by the number of photon. Therefore, the approved document also includes information on the practical realisation of a transition away from measuring radiometric and photometric values to measuring photon quantity.

1.1. Photometry and radiometry

Candela is the base unit of luminous intensity as a photometric value in the SI. The definition of a candela in the SI establishes the link between radiometric and photometric units. In 1979 at the 16th General Conference on Measures and Weights, the following definition of candela [*cd*] as the unit of luminous intensity was accepted [13]:

"The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} hertz and that has a radiant intensity in that direction of 1/683 Watt per steradian."

It follows from this that, in SI units, the spectral luminous efficiency K_{cd} of monochromatic radiation with a frequency of $540\cdot10^{12}$ Hz is equal to 683 cd·sr/W or lm/W exactly.

This definition is formulated using only physical terms and only for one frequency of electromagnetic radiation. The purpose of photometry is to measure radiation parameters in the visible spectrum in a way that the results correspond with the observer's visual perception of this radiation. Most light sources have a wide frequency spectrum. For this reason the International Commission on Illumination (CIE) established several weighting functions, called relative spectral luminous efficiency functions. They describe relative spectral sensitivity, or a reaction spectrum of an average human eye under certain observation conditions. These functions are expressed as dependencies on wavelength in standard air (dry air at 15 ˚C and 101325 Pa containing 0.03 % volume carbon dioxide) normalised relative to their maxima. The candela definition is intended to connect up these functions, setting their values at a specified frequency. The K_{cd} constant, together with the relative spectral luminous efficiency function brings together radiometric and photometric values in a unified metrological system.

In 2007, the *Bureau International des Poids et des Mesures* (BIPM) and CIPM (as it part) formed an agreement with the CIE, according to which it was confirmed that:

- CIPM (BIPM) is responsible for the definition of photometric units in the SI;
- CIE is responsible for standardisation of relative spectral luminous efficiency functions of the human eye.

Overall, the equation linking a preset radiometric value spectral distribution $X_{e,\lambda}(\lambda)$ with its corresponding photometric value X_{vx} is expressed as follows:

$$X_{v,x} = \frac{K_{cd}}{V_x(\lambda_a)} \int_\lambda X_{e,\lambda}(\lambda) V_x(\lambda) \cdot d\lambda, \qquad (1)$$

where λ_a = 555.017 nm is wavelength in standard air [3], which corresponds to the frequency specified in the candela definition, and lower index x indicates a CIE relative spectral luminous efficiency function. The most important of these visual perception functions, is relative spectral luminous efficiency for an observer's eye as it adapts to daylight vision condition $V(\lambda)$, tabulated by the CIE with an interval of 1 nm for the wavelength range (350–830) nm. Recently the CIE standardised the relative spectral luminous efficiency function for twilight sight (mesopic function). This function is intended to be used at luminance levels between those corresponding to day time sight conditions and those corresponding to night time vision conditions (eye's adaptation during twilight). This concluded the standardisation process for functions [14,15] connected with conditions of vision.

1.2. Photometry and photon quantity

Photon quantity are characteristics of optical radiation expressed through known numbers of photons or photon fluxes. Because of the dual nature of electromagnetic radiation, photometric and/or spectral energy values can be expressed using photon quantity.

For wavelengths in air, relations between the spectral energy value $X_{e,\lambda}(\lambda)$ at the corresponding wavelength, and coincident photon value $X_{p,\lambda}(\lambda)$ is expressed as follows:

$$X_{e,\lambda}(\lambda) = \frac{hc}{\lambda} \cdot n(\lambda) \cdot X_{p,\lambda}(\lambda), \qquad (2)$$

where h is Planck's constant, c is the speed of light in a vacuum, $n(\lambda)$ is the refraction spectral index of standard air.

Having combined equations (1) and (2), we obtain a general equation connecting photometric value $X_{v,x}$ and its corresponding photon value $X_{p,\lambda}(\lambda)$:

$$X_{v,x} = K_{p,x} \int_{\lambda} X_{p,\lambda}(\lambda) \frac{n(\lambda) V_x(\lambda)}{\lambda} d\lambda, \qquad (3)$$

where

$$K_{p,x} = \frac{K_{cd} hc}{V_x(\lambda_a)}, \qquad (4)$$

and $K_{p,x}$ is the transformation coefficient of photon quantity into photometric for the relative spectral luminous efficiency function $V_x(\lambda)$.

Photon quantity are especially important for the evaluation of illumination devices (ID) of the photosynthetic active radiation (PAR) [16.17]. In order to evaluate this, the photon number is correlated with the molecule number of the substance which absorbs them.

Avogadro's number ((N_A = 6.026 $\cdot 10^{23}$ mol $^{-1}$) represents the unit of photon flux [18] in the PAR interval. Thus photon flux Φ_{ph} at the wavelength λ in the PAR spectral range will be equal to:

$$\Phi_{ph}(\lambda) = \frac{N_{ph}}{N_A} = \frac{\Phi_e(\lambda)\lambda}{N_A hc}, \ [\mu\text{mol/s}], \qquad (5)$$

where photon number $N_{ph} = \Phi_e(\lambda)/E_{ph}(\lambda)$, i.e. it is equal to the relation of spectral radiation flux $\Phi_e(\lambda)$ to quantum energy of the corresponding wavelength $E_{ph}(\lambda) = hc/\lambda$.

2. REALISATION OF CANDELA AND DERIVATIVE UNITS OF RADIOMETRIC, PHOTOMETRIC AND PHOTON QUANTITY MEASUREMENTS

The existing methods of realising radiometric and photometric measurements units are described in more detail in [8]. As the definition of the candela connects photometric measurements units with radiometric ones, the practical implementation of photometric units is almost always based on the practical implementation of radiometric units.

Two main methods are usually used to implement radiometric units. They are the detector-based and the source-based methods, depending on what they are based on: a primary standard receiver, or a primary standard radiation source. The realisation of measurement units size of photon quantity, such as photon flux (photon number per second), or photon irradiance (photon number per second per unit area) for low levels of radiation fluxes can be achieved with radiometric methods based on a receiver or a source of radiation and describing transition from radiometric values to photon ones. However, single-photon sources can also be used and photon quantity can be obtained via a photon count. This third approach is referred to as the photon-based method.

The method of measuring using an absolute radiometer involves the principle of electric replacement (Electrical Substitution Radiometer – ESR), i.e. heating using optical radiation is compared with heating by electric power, which replaces the optical radiation. This well-known method is often applied with radiometers cooled to ultralow temperatures (<~ 20 K), where the influence of many sources of error significantly decreases. These devices are called cryogenic radiometers.

Predictable Quantum Efficiency Detectors (PQED) present a method based on a high-efficiency semiconductor material with small losses in a certain spectral interval of wavelengths. As a rule, this is based on a silicon photodiode which uses an exact method of transforming photons to electrons and registers the quantity of the incident optical radiation proceeding from measurement results of the generated photocurrent. This approach is initially based on the separate photodiode "self-calibration" principle, and it increased its importance after emergence of trap detectors with quantum efficiency close to one due to creation of radiation traps forming reflections from several photodiodes with electrically combined outputs, [3, 4, 18, 19].

An absolute source is a source, the optical radiation characteristic of which can be calculated based on the measurement results of other physical parameters, for example, thermodynamic temperature. Optical radiation generated by any other source can be measured by direct comparison with such an absolute source. There are two types of sources, which can be considered absolute under certain conditions:

- Model of Planck's radiator (black body model, Fig.1): For a cavity with a high thermal emissivity (very close to one), the radiated spectral radiance can be predicted using Planck's radiation law, com-

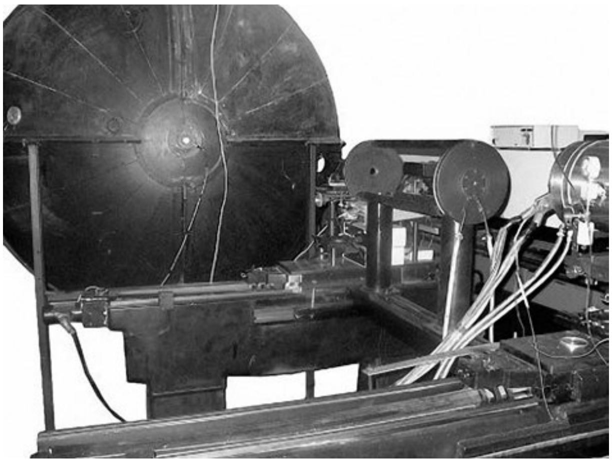

Fig.1. State Primary Standard of luminous intensity and luminous flux unit, VNIIOFI, Moscow [21]

ing from the thermodynamic (absolute) temperature of the cavity. In this case it can be traced back to the SI base temperature unit – Kelvin. For many fields of application requiring a high precision, cavity absolute temperature is determined using a calibrated radiometer with a colour filter (which is called a filtered radiometer). And in this it can be traced back to electric SI units. If the radiance of the source is constant in all directions, then having used a precise aperture placed in front of the Planck's radiator in a certain direction at a significant distance, the computed value of its spectral radiance can be transformed to a predicted spectral radiant intensity, spectral irradiance at a preset distance or to spectral flux distribution within a certain solid angle [20, 21].

- Electron accumulator ring generating synchrotron radiation, Fig.2: Electrons moving with relativistic velocities along circular trajectories generate synchrotron radiation. Under certain conditions, this source can be considered as absolute. In this case, the power of the synchrotron radiation beam generated by one electron moving along a circular trajectory with frequency ν [$W\cdot rad^{-1}$], can be predicted using Schwinger's equation based on the known and measured values of electrical and geometrical parameters. Any number of electrons, even one, can be accumulated without any changes in the configuration of the radiation spectrum. In this case, tracing can be to electric units and to SI units of length.
- Synchrotron radiation covers a big photon fluxes interval, up to 12 orders of magnitude, which allows bringing the photon flux in line with the sensitivity of the studied detector [22, 23].

Traceability in measurements based on the reproduction of photon quantity relies on the definition of candela being connected with photon quantity by means of photometric and radiometric values [8, 24]. Separate photons can be generated for by nonlinear materials, for example, as well as optical and electric sources of single photons, and can be counted by photo multipliers, one-photon impact avalanche and transit-time diodes, superconducting detectors nanowire based and phase transition detectors.

The most widespread method of photometric value measurement is based on the use of a standard photometric detector, the spectral sensitivity of which precisely corresponds to the necessary function of relative spectral luminous efficiency. The receiver (photometer and photometric head) has a precise aperture calibrated over the area (traceability to the SI length units) and a measured spectral sensitivity (traceability to the absolute radiometer [25]). Using the comparison method or direct measurements, the photometric unit is transferred to other light sources or to photometric heads with standard status, which become secondary standard photometric sources (or photometers) for transmission of the correspondent photometric value. In this case, traceability to the SI units is "detector-based", and hence to the electric SI units. This method usually requires additional measurements of the photometer's spectral sensitivity in order to determine

Fig. 2. Source of synchrotron radiation BESSY II, PTB, Berlin [22]

the quality of spectral correction of the receiver relative to the CIE relative spectral luminous efficiency function. To determine a photometer correction quality, one should know relative spectral characteristic of the measured light source [26, 32].

If photon quantity are measured in the process, then they can be transformed into the correspondent photometric values using equation (3).

Practically, all methods of determining photometric, energy and photon parameters result in traceability to the base units of the SI, Fig. 3.

3. EQUIPMENT OF TEST LABORATORIES FOR OPTICAL RADIOMETRIC MEASUREMENTS

Equipping and metrological support of accredited test laboratories and centres in the field of optical radiometry is integral to enabling modern energy efficient, ecologically sound illumination which provides a high quality environment.

The international lighting community pays a lot of attention to the uniformity of measurement, which can enable a reliable evaluation of lighting product parameters.

From October 2012 until August 2013, international laboratory comparisons *IC2013* of the measurements of illumination devices with light emitting diodes were prepared and undertaken by a group of international experts within the IEA 4E SSL Annex special programme of the International Energy Agency. These comparisons revealed some differences in the results of participant laboratories which were caused by measurement techniques, the equipment used and by choice of criteria for evaluation of measurement uncertainty [27, 28].

IEA 4E SSL Annex 2017 has declared a new initiative of international comparisons of test laboratories and centres covering measurements by goniophotometers, which is based on protocols of the CIE new standard [30]; there are a number of associated prototype documents including: European standard EN13032–4, IESNA LM79 standard, Korean standards KS C7653 and KS C7651, as well as other international and national materials.

The new CIE standard [29] proposes the following systems protocols to test characteristics of illumination devices (ID):

– Systems with integrating spheres: integrating sphere with a photometer, integrating sphere with a spectrometer;

– Goniophotometric systems: goniometer with a photometer (including near-field region goniophotometers with image photometers (luminance meters), goniometer with spectral radiometer, goniometer with three-channel colorimeter;

– Luminance meters (photo-electric and digital);

– Spectroradiometric installations with standard radiation sources to measure spectral characteristics of the tested ID in a preset observation geometry.

Measurements of small size devices, for which no luminous intensity distribution measurements are needed (for example, of LED lamps), are carried out using systems with integrating spheres. Measurements of luminaires, for which luminous intensity distribution data is needed, are carried out using goniophotometric systems. To analyse spectral and colour characteristics, sphere – spectrometer, goniometer – spectral radiometer (spectrometer) or goniometer – colorimeter systems are used.

The goniometer – colorimeter system is only recommended for the measurement of relative colour characteristics.

Spectroradiometric stands are used to determine absolute spectral characteristics of light sources (LS) and of illumination devices, as well as to calculate characteristics measured within certain geometries (observation angles), for example, to determine a blue light hazard radiance parameter L_b [30, 31].

All instruments making up the measurement system, as well as integrated system optical stands, should be verified (calibrated) with traceability to the SI units.

3.1. Requirements for integrated photometers

The spectral characteristics of photometers, luxmeters, photometric heads and luminance meters used within photometric installations should correspond to the function of relative spectral luminous efficiency of monochromatic radiation for $V(\lambda)$ curve, [36].

Total coefficient f_1' correction factor (sphere – photometer, goniophotometer, luxmeter) should not exceed 3 % [26, 32, 33].

If this requirement is met, spectral discrepancy only needs to be corrected for tested devices with colour light emitting diodes. This requirement can also be sidestepped if a correction for spectral discrepancy is assumed for each tested device. In this case, current f_1' values are added into the

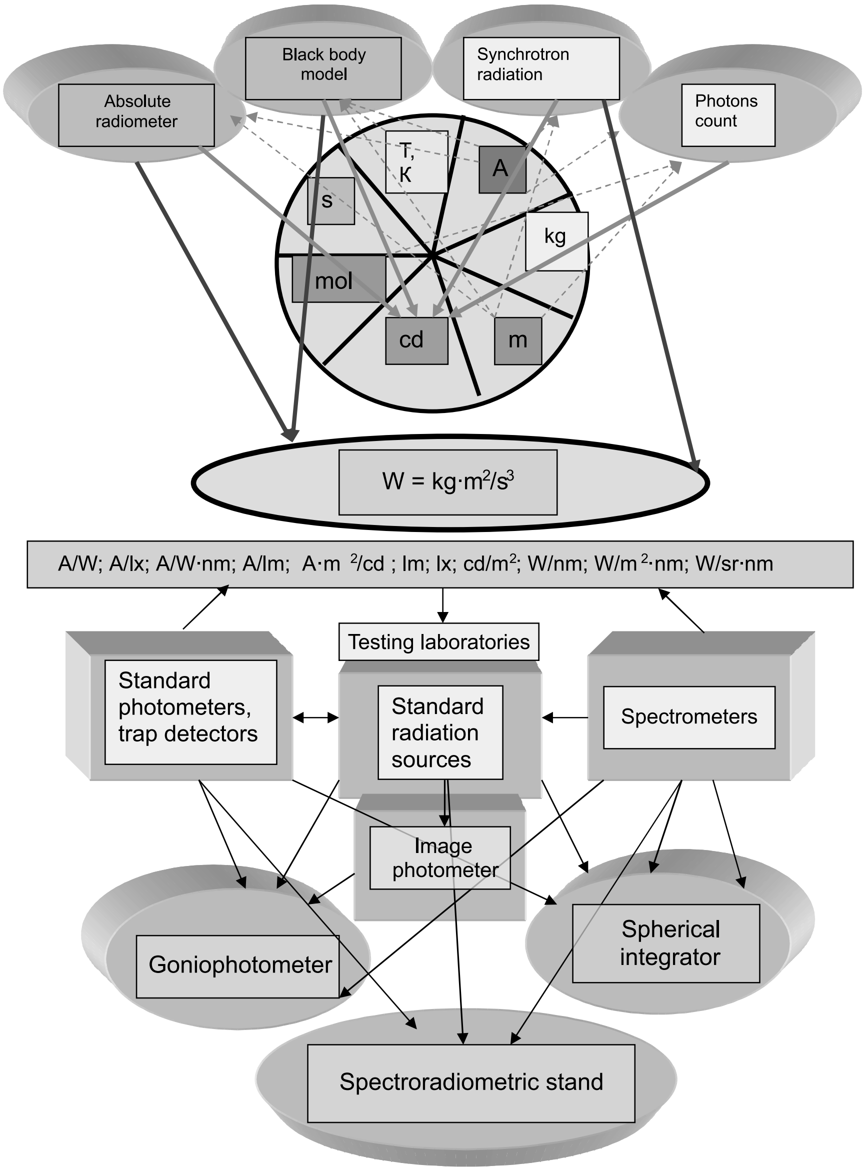

Fig.3. Traceability to the base units of the SI and transmission of unit size from primary and special standards of optical radiometry of incoherent radiation to measuring systems of testing laboratories

measurement protocol. If no correction is made for spectral discrepancy, its effect should be accounted for in the uncertainty calculations. Even if corrections are made, the impact should still be considered in the uncertainty calculations connected with correction quality under $V(\lambda)$ [34, 35].

Spectral light functions different from $V(\lambda)$ should be used when measuring photometric characteristics under night or twilight observation conditions [14, 15].

3.2. Integrating sphere

An integrating spheres should be equipped with auxiliary lamps for measuring self-absorption.

Self-absorption depends on the ratio of the tested device (TD) to the size of the sphere, on the TD and standard lamp configuration and size, as well as on TD reflection characteristics and on the sphere coating.

When the TD is installed in the centre of the sphere (4π-geometry), its surface area should be no more than 2 % of the area of the sphere's inner surface. When the TD is installed at the opening of the sphere (2π-geometry), the opening diameter should not exceed 1/3 of the sphere diameter. When the TD is installed at the centre of the sphere (4π-geometry), its long axis should align with the line drawn between the photometric head detector and the sphere's centre so that the screen size is minimised.

The inner coating of the sphere should be diffusing, not spectrally selective and not fluorescent. For the measurements, it is recommended to use spheres with a coating reflection factor of no less than 90 %. The light source holder and ancillary equipment inside the sphere should be as small as possible and have coating of the maximum possible diffuse reflection. To enable cosine correction, a diffuse nozzle or an auxiliary sphere is installed on the input opening of the photometric head or spectral radiometer. Measurement reproducibility when closing and opening the sphere should be within ± 0.5 %. Change in sphere sensitivity between calibrations is permissible at no more than 0.5 %.

Calibration of the integrating sphere is performed using a luminous flux standard lamp. Its luminous intensity spatial distribution should be similar to that of the test device. Any difference between the luminous intensity distributions should be accounted for in the uncertainty budget.

3.2.1. Sphere – spectral radiometer system

Sphere – spectral radiometer system should be calibrated using a full radiation flux spectral distribution standard with traceability to the SI units. In the event that no such calibration standard is available, the calibration can be done using a standard lamp of irradiance spectral concentration and of a standard lamp of full luminous flux, with traceability to SI units. In this case the used method and related parameters (for example, angular uniformity of spectral distribution, or correlated colour temperature of the standard lamp) should be noted in the measurement protocol. It is imperative to perform a joint calibration of the sphere system together with the spectral radiometer. The spectral radiometer used in the sphere – spectral radiometer system should meet the following requirements:

– Interval of wavelengths between 380 and 780 nm;

– Uncertainty of wavelength set using a spectral radiometer should be no more than 0.5 nm with $k = 2$;

– Spectral width of the slit and scanning pitch should be no more than 5 nm.

The spectral radiometer should have a linear response relative to incoming radiation at each wavelength of the visible interval. The impact of a non-linear response and inner light scattering should be accounted for as an uncertainty.

The auxiliary lamp to measure self-absorption should have a radiation spectrum in the visible wavelength range.

3.2.2. Sphere – photometer system

A sphere – photometer system should be calibrated using the full luminous flux standard with traceability to SI units [36]. The standard lamp and tested device should have similar radiation spectral distributions.

A sphere – photometer system should have a relative spectral distribution corresponding to the function of the relative spectral luminous efficiency of monochromatic radiation for daylight $V(\lambda)$ curve (see also requirements listed in 3.1.). If spectral correction is necessary, the correction factor is calculated. Relative actinic coefficient is performed based on the data on TD relative spectral distribution and relative spectral sensitivity of the system, i.e. accounting for relative spectral characteristic of the photometric head and contribution of relative spectral distribution of the sphere function $\rho(\lambda)/(1-\rho(\lambda))$, where $\rho(\lambda)$ is spectral reflection factor of the sphere's inner surface material [37].

It is recommended that the auxiliary lamp to measure self-absorption would have a radiation spectrum similar to the TD spectrum, especially when measuring one-colour modules.

3.3. Goniophotometers

A goniophotometer should have scanning angular interval corresponding to the full solid angle, in which the TD radiates light. It is especially important to measure full luminous flux.

Angular TD adjustment should accurate within ± 0.5º of the preset direction. The angular display should have a resolution no less than 0.1º.

When measuring the spatial distribution of luminous intensity, the radiation source is considered to be a point light source. Luminous intensity is obtained from the measured illuminance according to the inverse-square law.

For far-field goniophotometers, measurements are taken at the following distances:

– For a TD with a distribution close to cosine (Lambert distribution with radiation angle ≥ 90º), in all *C-planes*: $\geq 5d$;

– For a TD with a wide angular distribution, different from cosine (radiation angle ≥ 60º), in some *C-planes*: ≥ *10d*;

– For a TD with a narrow angular distribution, a high gradient luminous intensity distribution, when the photometer (spectral radiometer) signal must be protected from reflected light glares: ≥ *15d*;

– For a TD with large unlit areas between the lighting surfaces: ≥ *15 (d+s)*, where *d* is the maximum size of the radiating RD surface, and *s* is the biggest distance between two neighbour lighting surfaces.

For near-field goniophotometers, the distance is not normalised.

Full luminous flux is calculated by integrating the illuminance distribution. Therefore, measurement does not require the use of far-field region goniophotometers.

Goniophotometers with a dead zone of more than 0.1 *sr* of the solid angle can be used to measure full luminous flux as long as corrections are made in the calculations.

3.3.1. Goniophotometer – photometric head system

Relative spectral distribution of a photometric head should correspond to the function of relative spectral luminous efficiency of monochromatic radiation for the daylight $V(\lambda)$ curve. If necessary, a spectral correction factor is applied, based on known values of the TD radiation relative spectral distribution and of the photometric head relative spectral sensitivity. The correction coefficient for spectral discrepancy corresponds to the CIE standard [34].

The goniophotometer should be calibrated using a luminous intensity standard or illuminance standard with traceability to the SI units [37]. If the full luminous flux is measured, then calibration requires a standard of full luminous flux with traceability to the SI units.

The dead angular area of the goniophotometer should not influence the measurement results of the full luminous flux standard lamp.

3.3.2. Goniophotometer – spectral radiometer system

A goniophotometer – spectral radiometer system should be calibrated against a radiant intensity spectral distribution standard or irradiance spectral standard with traceability to the SI units [38].

When using a system to measure the full luminous flux or full spectral luminous flux, calibration requires the full spectral luminous flux standard with traceability to the SI units. The dead angular area of the system should not influence the measurement results of the full spectral luminous flux standard lamp.

The spectral radiometer used in the goniophotometer – spectral radiometric system should meet the following requirements: wavelength interval between 380 and 780 nm; wavelength determination uncertainty should be no more than 0.5 nm with k = 2; spectral width of the slit and scan pitch should be no more than 5 nm. The spectral radiometer should have a linear response to incoming radiation for each wavelength of the visible interval. Nonlinearity and inner light scattering should be accounted for as contributing to the uncertainty of the measurement.

3.3.3. Goniophotometer – colorimeter system

A goniophotometer – colorimeter based system should include three-channel colorimetric heads to measure colour co-ordinates *X*, *Y*, *Z*, which should have spectral sensitivity correspondant to the CIE standard colour functions. The *Y* channel should also meet the requirements for goniophotometer – photometric head system (see section 3.3.1).

If these conditions are not met, then the system can be only used to measure colour differences.

3.4. Luminance meters

The measurements need photo-electric luminance meters, which measure point luminance, and digital luminance meters, which capture surface luminance image distribution. The luminance meters are calibrated using a luminance standard with traceability to the SI units [37].

The relative spectral distribution of a luminance meter should correspond to the function of relative spectral luminous efficiency of monochromatic radiation for the daylight $V(\lambda)$ curve [36].

If necessary, a spectral correction factor applied based on known values of relative spectral distribution of TD radiation and the photometer relative spectral sensitivity. The correction factor of spectral discrepancy from *V (λ)* function is determined according to the formulas given in [33, 39].

When measuring with a digital luminance meter, measurement uncertainty can be estimated by comparing results to the luminance distribution of a typical LED device using a traditional photoelectric luminance meter.

3.4.1. Image luminance meters [40, 41, 42]

The main purpose of digital luminance meters (imaging luminance measurement device) (ILMD) is to measure a projection of spatial luminance distribution of extended sources and of illuminated surfaces.

A luminance meter forming an image, i.e. image luminance measurement device or ILMD, is a device consisting of an image detector (for example, charge coupled device CCD), a photometric correcting filter, a lens, electronic components (analogue-digital converter, a sample-hold circuit, built-in software for information processing and a display). The devices differ by calibration types.

Type I ILMD: Only luminance calibration. Each pixel (*i, j*) of luminance image *L* (*i, j*) only contains information on the luminance observed within the scene.

Geometric information for the image evaluation is not required.

Type II ILMD: Each pixel (*i, j*) of luminance image *L* (*i, j*) contains both the scene luminance value, and accompanying information on direction ϑc (i, j)/φc (i, j) and location of $x_s(i, j)/y_s(i, j)$, as well as on visible solid angles $\Delta\Omega_{Pixel}$ (i, j). For ILMDs of this type, both photometric and geometric calibrations are necessary.

The properties of "classical" luminance meters are described in [33]. For ILMDs some additional features need to be considered:

- Measurements and evaluations are usually performed by computer programs. Conversion of the physical signal (collected images) into luminance values can be complex, and sometimes processing and compressing images algorithms are used (for example, to reduce the size of the data).
- ILMDs have a large number of more or less independent receivers, called pixels. If the system is seen as a totality of separate receivers, then each receiver has its own characteristics. However in practice these pixels are combined (mechanically or mathematically) to form several measurement areas (evaluation areas).
- Some available ILMDs enable easy substitution of optical system parameters (changes in focal length, focus, aperture, lenses and neutral colour filters).
- Generally, the parameters serving to describe the ILMD, refer to a specific configuration (a stable focal length, a constant focus, invariable apertures), which should be displayed together with the quality indicators.
- A luminance image is a totality of luminance values *Y (i, j)* measured by the image detector which is a part of the ILMD with (*N·M)* sensitive elements (pixels).
- ILMDs should be calibrated by means of luminance standards using a uniform lighting Lambert surface, the size of which significantly exceeds the object field being a part of the evaluation area. The luminance standard used for the calibration is itself calibrated as an intermediate standard, by means of a calibrated luminance meter by the replacement method (a receiver calibrates a receiver) or using a photometric head in the illuminance mode with an additional precise aperture on a lighting surface of the luminance standard.
- An ILMD can be also calibrated using a source with a known spectral distribution of radiation, essentially different from radiation of a black body (for example, for colour LEDs).
- In this case, the spectral sensitivity of the measuring device should differ significantly from zero in the whole spectral interval, which will allow determining the mismatch correction factor.
- Correction coefficients can also be calculated based on the spectroradiometric measurement results. Spectral standards of radiance are required for this. Using the calibration data of these standards, (integral) photometric values should be computed according to their definitions. The correlation between he standards' spectral characteristics need to be considered here, as this will impact the uncertainty of the measurement.
- When calculating measurement uncertainty, the distribution of the luminance standard luminous intensity needs ot be accounted for, especially in the event of large angles of the photometer measurement fields, or if the replacement method is implemented using various angles of measurement fields of the intermediate standard and of the calibrated luminance meter.

• Photometers should be calibrated regularly within the manufacturer recommended time frame, or if there are suspicions that the device's characteristics changed.

3.5. Goniophotometer of near field region [42]

The concept of the fundamental phenomenological photometry is based on the values ***of luminous flux Φ, luminous intensity I = dΦ/dw, illuminance E = dΦ/dA,*** considered with implementing conditions (within a preset approximation) of the law of inverse-squares, i.e. the conditions at which the receiver and the radiation source can be considered as point. In practice, we deal with extended light sources and with light devices, for which photometric characteristic measurement requires long distances. At the same time, fundamental photometry deals with the concept of ***luminance L = dΦ/dwdAcosθ.*** Luminance is a characteristic of the luminant physical surface and does not depend on distance. The light field theory proposed by A.A. Gershun in the early 1930s, and his telecentric method of luminous intensity measurement, allowed interpreting the luminance concept having attributed it an infinitely small solid angle equivalent to a geometrical ray.

So, an elementary cone ***dw*** can be considered as an infinitely thin ray with a differential section ***dAcosθ.*** Luminance ***L*** has the following ratio to luminous intensity: ***L=dI/dAcosθ***, where the differentiation area surrounds the point light source. Similarly, luminance can be expressed via illuminance: ***L=dE/dwcosθ.*** Then illuminance expression ***E*** will be: $E = \int_w L\cos\theta dw$. The integration is implemented over the entire image of the hemisphere crossed by a solid angle ***dw*** (an elementary cone). The latter illuminance expression is useful, because it allows computing illuminance at a point on a surface created by an extended source of luminance distribution for a differential source surface is known (an elementary cone being a beam of rays).

There are physical light sources the nature, which do not have a certain luminant surface since they have volume, for example, plasma. Another example is light from the atmospheric scattering of solar radiation.

When considering radiation sources of volume, an important feature is real luminance or image luminance. In other words, luminance at a point in space and in a preset direction can be defined as luminous flux in relation to the unit of area of this direction within a single-unit solid angle. So instead of considering the luminant surface, we look at the light field around an observer (objective or visual), and the fundamental luminance concept is used as a geometric beam of rays for a comprehensive description of spatial luminance distribution from an extended light source.

Gershun's light field theory is broadly applied today: 3D computer graphics and specialised software enable calculating and building illuminance at any point of any surface in 3D space, if the luminance of all rays crossing this point is known [43].

A practical application of the Gershun's theory is the technique for determining luminance of an imaginary plane around an extended light source using a near field goniophotometer, which includes a goniometer and a photometer as a luminance meter, sequentially measuring luminance up to 250,000 geometric rays (spatial cones) at any point in space. The luminance meter is installed on a moving arm, which rotates around the illumination device in the vertical plane. The luminaire can rotate in the horizontal plane (Fig. 4). The luminance measurement device is a CCD video camera, adjusted according to relative spectral luminous efficiency and equipped with a set of lenses. Selecting the corresponding lens, the camera is focused on the luminaire light body. Each sensitive matrix element

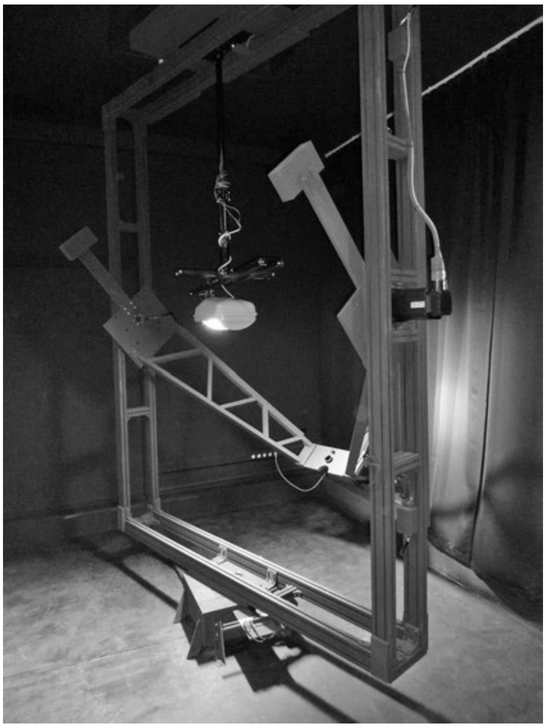

Fig 4. Near field goniophotometer RIGO 801 (VNISI named after S.I. Vavilov)

measures luminance of a pyramidal volume in the preset direction. Thus a digital iluminance meter forming the image is a part of the near field region goniophotometer (Fig. 4.).

3.6. Spectroradiometric measuring system

A spectroradiometric measuring system can be based upon an optical stand, for example an optical bench like OCK 2. The spectral radiometer used as part of the measuring system can be based on a CCD matrix at the output of a dispersive circuit; it can be scanning with a double monochromator. In any case, the spectral radiometer is the comparator in the circuit of spectral distribution of the radiation standard source and of the tested device. Using mini spectrometer allows for rapid measuring techniques, but measurement accuracy decreases. The scanning spectrometer is used for precise absolute measurements of irradiance, radiance, radiant intensity or radiation flux spectral distribution. To compare each of these values with a standard value, additional equipment is required: a special optical system for image projection, or input slit illumination mode is needed, or an input into fibre-optical path of the mini spectrometer with a CCD matrix at the output is necessary (Fig. 5). Measurement units are traced to Planck's radiator, i.e. to thermodynamic temperature T, K.

4. MEASUREMENTS OF PHOTOMETRIC CHARACTERISTICS OF MODERN TDS (LED LAMPS, LED MODULES, LED LUMINAIRES)

When testing modern illumination devices, the following luminous and colour parameters are reported: full luminous flux, light efficacy, partial luminous flux, luminous intensity distribution, luminance and illuminance distribution, colour co-ordinates, correlated colour temperature (CCT) and colour rendition index.

For each, measurement error and uncertainty is analysed, and the total error is calculated taking into account tolerance and acceptance intervals for uncertainty limits with a confidence probability of 95 %. The tolerance interval includes errors connected with the standard test conditions (for example, temperature in the laboratory, circuit power supply voltage, etc.).

Particular attention must be given to tolerance levels when the manufacturer establishes the data reported in the specification ID of each specific type [29, 44].

4.1. Full luminous flux

A method for luminous flux measurement is selected depending on the geometric parameters of the tested device and on the characteristics which need to be measured. Measurement methods using an integrating sphere with a photometric head or a spectral radiometer can be applied.

Determination of luminous flux can be performed by the measured distribution of luminous intensity or illuminance distribution and by photometric measurement distance.

In the integrating sphere the following provisions apply to TD installation:

– 4π-geometry is applied for all light source types, including LED devices. The TD is installed at the centre of the sphere in the working position. If possible, the TD is oriented so that minimum direct light is directed to the screen. Linear sources should

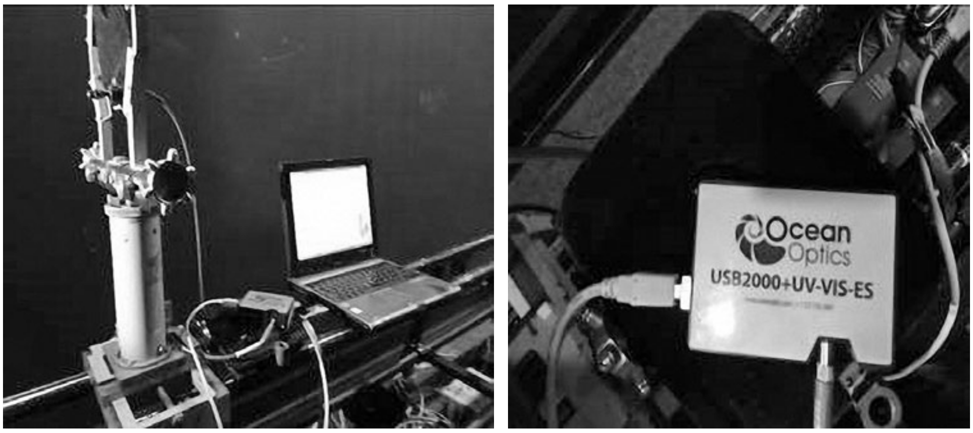

Fig. 5. Elements of a spectroradiometric stand with a mini spectrometer (VNISI named after S.I. Vavilov)

be installed so that their axis aligns with the line drawn between the centres of the photometric head and the sphere. The sphere is calibrated by means of a luminous flux standard lamp, which is installed at the same position as the TD.

– TDs are installed to operate on the wall of the sphere. 2π-geometry is applied for light sources, including LED devices with hemispherical and directed distribution without inverse radiation. A screen is used to prevent direct illumination of the photodetector by the light source. The sphere is calibrated using a luminous flux standard lamp with hemispherical distribution, which is installed in the same position as the TD.

If the TD and the luminous flux standard lamp have different size and reflecting characteristics, then a self-absorption correction coefficient should be applied using an auxiliary lamp.

For the sphere – spectral radiometer system, measurement of the auxiliary lamp and correction of self-absorption are performed based on spectral measurements.

Differences in the angular intensity distribution of the TD and luminous flux standard lamp should be estimated and corrected.

4.2. Partial luminous flux

The relationship between full and partial luminous flux can be measured with a goniophotometer. To determine cone angle α, partial luminous flux is obtained from the sum of intensity distributions $I(\theta_i, \varphi_j)$ measured with scanning pitch $\Delta\theta$ and $\Delta\varphi$.

Full luminous flux is measured using an integrating sphere, and partial luminous flux is determined as the product of the fluxes relation by the full luminous flux value.

When determining partial luminous flux in cone angles of 90º or more, the measurements should be made from a scanning pitch no more than 5º for angles θ (angle γ in co-ordinates system C, γ) and no more than 45º for angles φ (angle C in co-ordinates system C, γ). A lesser angular pitch of scanning can be applied for TDs of a special application (for example, for street luminaires).

4.3. Luminous efficacy

Luminous efficacy η_v is the relation of luminous flux Φ radiated by an LED device, to the consumed electric power P_{tot}.

$$\eta_v = \Phi / P_{tot} \quad (5)$$

Luminous flux measurement techniques are described above, and a number of special requirements to characteristics of the power supplies and of the electric parameters of illumination devices apply when testing and measuring [29]:

– AC/DC voltage, current and power should be measured with precise equipment;

– The calibration error of an AC voltmeter should be no more than 0.2 %, and te calibration error of a DC voltmeter should be no more than 0.1 %;

– The calibration error of the power measurement instrument (power analyser) for alternating current should be no more than 0.5 % with a frequency of about 100 kHz; lower frequencies (5 kHz or 30 kHz) are acceptable if there are no components with frequency higher than 30 kHz;

– Total coefficient of harmonious distortions for voltage measured at the tested device should not exceed 1.5 %. If the power factor exceeds 0.9, this coefficient should be no more than 3 %.

4.4. Luminous intensity distribution

When measuring luminous intensity spatial distribution, except especially stipulated cases, the C, γ co-ordinates system is used [45].

The angular interval between indications of vertical plane luminous intensity and the angular interval between neighbour vertical planes should be such that the obtained luminous intensity distribution allows for an interpolation of the measurement results with satisfactory accuracy. The plane number is determined by the nature of the distribution (symmetric or non-uniform) and by ultimate goal of the measurement. Luminous intensity distribution measurements are made using a goniophotometer.

4.5. Axial luminous intensity and radiation angle

When determining luminous intensity distribution using a goniophotometer, direction (0.0) usually aligns with the optical axis of the radiation source. The axis passes through the photometric centre and is perpendicular to the light emitting plane (except for special requirements of the manufacturer).

Axial luminous intensity is determined towards the observed radiation angle (i.e. the axis, around which luminous the intensity distribution is almost symmetric), and the radiation angle is estimated around the observed optical axis of the ray.

4.6. Luminance measurement

When luminous surfaces are sufficiently uniform, the following measurement approaches can be used:

– Measuring average luminance of the whole luminaire in one or several directions by measuring luminous intensity (its distribution) with a goniophotometer, and then calculating average luminance by dividing luminous intensity by the illuminated surface area;

– The luminance spot measurement method, which is used to evaluate the spatial irregularity of luminance by large street luminaires [45].

The average luminance of small sites (luminance spots) on the luminous surface of a luminaire is measured in one or several directions. Maximum and minimum luminance values are usually set. The number and position of these points should be specified in the regulating documents. The measurements are carried out by means of a goniophotometer in a preset direction or using a luminance meter measuring average luminance at each spot. This method is applied for LED luminaires, which do not have a scattering coating that is a sum of point light sources.

5. MEASUREMENT OF COLORIMETRIC CHARACTERISTICS OF MODERN TDS (LED LAMPS, LED MODULES AND LED LUMINAIRES)

Spectral radiometers are used to measure colorimetric characteristics. Three-channel colorimeters cannot measure absolute colorimetric values with sufficient accuracy. Therefore they can be only used to determine colour differences in different directions.

Values of colorimetric characteristics of LED lamps, modules and luminaires may have a range of angles.

Colorimetric or spectral measurements are taken in the following geometries: along a preset direction, determination of a directed distribution using goniometer – colorimeter, or goniometer – spectral radiometer system. Spatially averaged measurement results can be obtained using the following methods:

– Measurement of full luminous flux using a sphere – spectral radiometer system with a subsequent recalculation into spatially averaged colorimetric characteristics;

– Measurement of radiation flux spectral distribution using goniometer – spectral radiometer system with a recalculation of these measurements into full luminous flux and spatially averaged colorimetric characteristics;

– Measurement of colour co-ordinates $X(\theta, \varphi)$, $Y(\theta, \varphi)$, $Z(\theta, \varphi)$ by means of goniometer – colorimeter system. Spatially integrated colour co-ordinates are calculated using the formulae:

$$X = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} X(\theta,\phi) \sin\theta d\theta d\phi \quad (6)$$

$$Y = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} Y(\theta,\phi) \sin\theta d\theta d\phi \quad (7)$$

$$Z = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} Z(\theta,\phi) \sin\theta d\theta d\phi \quad (8)$$

Colour co-ordinates, correlated colour temperature and other colorimetric characteristics are calculated using colour co-ordinates.

Colour rendition index can be only obtained using spectroradiometric methods [46].

5.1. Correlated colour temperature (for white LED radiation sources)

Chromaticity can be characterised by correlated colour temperature and by a colour difference parameter D_{uv}, which corresponds to a certain distance from the Planck's radiator curve in the CIE co-ordinates system (u', 2/3v'). This distance is positive for points over the curve and negative for points under the curve. Calculations of correlated colour temperature are made according to the CIE recommendations [47, 48].

5.2. Angular colour uniformity

Angular colour uniformity is determined as the greatest deviation of colour co-ordinates (u',v') of a LED radiation source in different directions from spatially averaged colour co-ordinates (u'_a, v'_a) and calculated using the formula:

$$\Delta_{u',v'} = \sqrt{(u' - u'_a)^2 + (v' - v'_a)^2} \qquad (9)$$

Colour co-ordinates (u', v') are measured with a goniometer – colorimeter system or goniometer – spectral radiometer system with a vertical angle interval of no more than 10º (2.5º is recommended) and with a horizontal angle interval of no more than 90º (22.5º is recommended). For reflecting lamps, angular pitch should be no more than 1/10 of the radiation angle (diameter of the cone radiating more than 1/2 of the intensity maximum) but no more than 10º. Measurement data at points where the luminous intensity is less than 10 % of the maximum, can be ignored for the calculations.

Average values of colour co-ordinates (u'_a, v'_a) are obtained using a goniometer – colorimeter systems measurements and calculations according to formulae 6–8.

6. ERRORS (UNCERTAINTIES) OF THE MEASUREMENTS

For all measured characteristics an expanded uncertainty is calculated at 95 % confidence. Expanded uncertainty is determined to two significant figures.

Each test report should include information on uncertainty values of the measured parameters and test conditions [29].

Test laboratories should have a detailed uncertainty budget for similar product types. If such an uncertainty budget is calculated for several products, the parameters of which have a known interval (for example, colour temperature is between 2700K and 4000K), then the maximum uncertainty value is set within the interval.

Correction of the test results can be made using the characteristics of tested device, but not those of a similar product.

For luminous intensity distribution, measurement uncertainty should be estimated at least in one direction, in which luminous intensity is sufficiently uniform. Set angle uncertainty (including the TD position in the goniometer) should be shown separately.

For luminance distribution, measurement uncertainty should reported in at least one point, where luminance distribution is more or less uniform.

In the total uncertainty budget, the following factors should be accounted for:

– Accuracy of the set temperature and uncertainty of the temperature measurement;

– Accuracy of the set electric parameters and uncertainty of electric measurements (power supply, electric measurement devices);

– TD radiation ripple;

– Calibration standard (data from the calibration certificate);

– Performance data of the calibration standard (ageing, electric measurements, calibration process);

– Linearity of the measuring devices;

– Reproducibility and repeatability.

For all measurements, the contribution to the uncertainty budget of both the measuring system and technique, but also of the specific TD and its characteristics should be considered.

Besides these parameters, the factors given in Table 1 should be considered as part of the uncertainty budget when measuring light and colour characteristics.

Furthermore, the following factors must also be considered as part of the uncertainty budget:

– bandwidth of the alternating current power measuring instrument (influence, correction);

– input resistance of the alternating current power measuring instrument.

A correlation between luminous flux and electric power values should be applied to evaluate a decrease of the measurement uncertainty. For example, if the consumed current influences both the luminous flux of the tested device, and electric power in the same direction and with the same sensitivity, then this factor can be disregarded when evaluating the uncertainty of the light efficacy measurement.

A general description of how to determine uncertainty in photometry is given in [49].

7. CONCLUSION

1. At the turn of the century the International Committee for Weights and Measures together with the world scientific community undertook a major programme to redefine the main units of the SI system based on physical constants and their photon nature, which increases reproduction and trace-

Table 1. Factors determining total error of the method

Determined characteristics	Equipment used	Error components
Luminous flux, luminous intensity, luminance	Classical goniophotometer	– diffused light (spatial); – TD installation accuracy; – spectral discrepancy; – irregularity of the detector receiving site; – cosine error of the radiation receiver; – uncertainty of distance measurement, if using illuminance measurement mode; – irregularity (planeness) of mirrors and effects of polarisation; – spectral reflection from mirrors;
Luminous flux	Sphere – photometer	- self-absorption in the sphere; – thermal mode; – heterogeneity of the sphere surface reflection factor; – reflections within the sphere; – spectral discrepancy (detector + sphere, differences of spectral distribution of the standard source and TD); – measurement reproducibility when opening and closing the sphere; – stability of transformation factor of the sphere between calibrations; – cosine error of the photometric head; – fluorescence effect of the sphere coating;
Luminous flux, luminous intensity distribution, axial luminous intensity, radiation flux spectral distribution, luminance, luminance distribution	Sphere – spectral radiometer	– self-absorption in the sphere; – thermal mode; – heterogeneity of the sphere surface reflection factor; – reflections within the sphere; – spatial heterogeneity of sensitivity; – error in the set wavelength; – diffused light in the spectral radiometer; – spectral interval of the spectrometer; – measurement reproducibility when opening and closing the sphere; – stability of the transformation factor of the sphere between calibrations; – cosine error of the photometric head; – fluorescence effect of the sphere coating;
Luminous flux, luminous intensity distribution, axial luminous intensity, spectral distribution of radiation flux, luminance, luminance distribution	Goniophotometer – and spectral radiometer Near field goniophotometer	– uniformity of mirrors and the influence of polarisation; – spectral reflectiveness of the mirrors; – diffused light (spatial); – TD installation accuracy; – receiving site of the detector; – cosine error; – accuracy of the wave length set; – inner scattering of the spectral radiometer; – spectral width of the spectral radiometer slit; – uncertainty of the distance measurement, if the spectral radiometer is calibrated according to the irradiance spectral concentration standard; – uncertainty caused by mirror reflection, if the spectral radiometer is calibrated according to the standard of radiance spectral concentration

Determined characteristics	Equipment used	Error components
Colour characteristics	Sphere spectral radiometer, goniophotometer – spectral radiometer	– correlations connected with colour temperature measurement uncertainty of calibration source of radiation; – inner scattering of the spectral radiometer; – spectral width of the spectral radiometer slit; – accuracy of the set wavelength; – linearity in the dynamic interval of the whole spectral interval

ability accuracy and precision for correspondent values and measurement units as a whole.

2. The 1979 definition of the candela provides a practical value of luminous efficiency for a function of average daytime human vision at a wavelength of 555 nm. The candela, as a base unit of the SI system, remains the measurement unit of luminous intensity – an effective value.

3. Modern lighting equipment has made it necessary to consider the mechanisms of visual perception in more detail, for example when illuminating streets and roads using LED illumination devices, and to introduce mesopic photometry into the evaluation of illumination, primarily for roads.

4. The use of illumination devices with LEDs has led to a greater number of requirements for test equipment for accuracy, for absolute photometry methods only, for the prevailing spectroradiometric approach as compared to detector based photometry in the field of optical radiometry.

5. Implementing the spectroradiometric approach in photometry is difficult as there are no standard light sources of radiation flux spectral concentration available in world practice. These are necessary for test laboratories, because any spectral radiometer forming part of the goniometer, of a sphere or of a spectroradiometric stand, can only be a comparator of spectral characteristics of standard sources and tested devices.

6. Considering the realities of modern photometry from the point of view real practice in Russia, it is importnat to note that the test system as a whole is comprised foreign equipment, which needs to be imported, certified, added to the measuring instrument register of the Russian Federation and annually calibrated. This raises the price of the lighting product test procedure significantly.

7. Special attention must be paid to the domestic measurement instruments industry in photometry and colorimetry. Russian manufacturers and developers of modern information and measuring systems, as well as of precise instruments, require assistance of the Russian lighting industry in order

to be equipped with their products.

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DEVELOPMENT OF NEW PHOTOMETRIC STANDARDS BASED ON HIGH POWER LEDs

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ABSTRACT

The paper describes the study design and results on stability and photometric characteristics of new powerful (> 10 W) thermally stabilised LED standard light sources for transmission of luminous flux and luminous intensity units, and in the long term full radiation flux.

Keywords: light emitting diode (LED), Chip-On-Board (COB), luminous intensity, luminous intensity spatial distribution, luminous flux, temperature stabilisation with feedback

1. INTRODUCTION

In the recent past and even today, incandescent lamps are widely used for transfer of luminous intensity and luminous flux unit size. Use of incandescent and halogen lamps is associated with certain difficulties: it is difficult to find and select standard specimens with required parameters of stability and luminous intensity or levels of luminous flux; it is not possible to use one standard specimen for various levels of luminous flux with various parameters of power supply. In addition, the production of incandescent lamps continually decreases as the LED industry develops [1]. The use of thermally stabilised LEDs has an important advantage for companies manufacturing LED based products. When product quality control is based on LEDs, calibration of the measurement equipment using LEDs with similar spectral composition allows increasing the measurement accuracy without time-consuming spectral measurements and, hence, without increasing time for the processing of results[2–4].

To replace lamps like SIS40–100, SIS107–500, SIS107–1000, SIP 24–10, SIP 107–500, SIP107–1000 and SIP 107–1500, which are traditional luminous standards in Russia, with standard light sources – thermally stabilised LEDs developed at the VNIIOFI are proposed.

2. SELECTION OF LIGHT EMITTING DIODES

The structure of the thermally stabilising case for the LED was developed in such a way that when changing LED types during production, the manufacturer could replace them with any light emitting diode. This will make it possible for manufacturers of lighting and other LED based devices to change a set of standard calibration specimens in the shortest possible time.

LEDs of different power and spectral composition were selected as experimental samples.

Experiments for the study of light parameter stability were conducted using specimens with the following electric powers: 1 W, 10 W, 36 W and 78 W. The samples were selected to understand different methods of removing heat: LEDs of 1 W and 10 W with aluminium heat sink, and LEDs of 36 W and 78 W with ceramic heat sink. Before assembling the thermally stabilised source structures, the LEDs underwent preliminary annealing for 250 hours [5.6]. After final assembly of the structures, the LEDs were annealed for an additional 100 hours in operating mode (with the temperature stabilisation).

3. CONSTRUCTION DESCRIPTION

3.1. Light source (LS)

The structure provides for two types of standard specimens: with and without optical elements homogenising spatial distribution of radiant intensity spectral concentration. Application of optical elements to decrease non-uniformity of the spatial distribution of radiant intensity spectral concentration is caused by the necessity to calibrate goniophotometers using these standard specimens.

A platinum thermal resistor *Pt-1000* was selected as the diode temperature control detector. This choice is based on its high stability and reproducibility. Peltier elements are used for active temperature stabilisation.

The radiators selected consist of industrially made products according to the expected dissipation power; they are finally treated later in the structure assembly process. The inner heat-conducting elements are made of copper. The output aperture diaphragm is manufactured out of brass. The external case is made of plastic.

LS structures with optical elements and without optical elements are presented in Fig. 1.

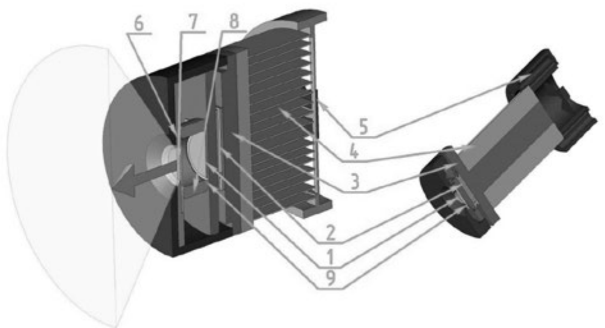

Fig. 1. A device for thermally stabilised LSs based on *COB (chip-on-board)* LEDs with optical elements (left) and without optical elements (right)
1 – *COB* LED; 2 – Peltier element; 3 – copper base for Peltier element; 4 – radiator; 5 – fan; 6 – aperture diaphragm; 7 – matte glass; 8 – polytetrafluorethylene tube; 9 – point with a known thermal resistance before LED crystals (a thermal resistor is installed at this point)

COB LED1 is placed on a copper plate, which is the thermal accumulator in order to improve parameters of thermal stabilisation and smooth temperature change for the LED itself. To provide angular uniformity of radiation spectral characteristics in the first type LS structure (Fig. 1, at the left), special optical elements are applied as tubes of polytetrafluorethylene (plastic fluor) 8 and of MC-23 glass 7 with matting. The aperture diaphragm 6 is the LS output window. In the structure with additional optical elements (Fig. 1, on the left), the diameter of the output window is 20 mm; in the second type, the diameter of the output window depends on the LED used. The copper plate with the LED is placed on Peltier element 2, which provides for the LED temperature adjustment. The Peltier element is installed on copper plate 3 with radiator 4, which is actively cooled by fan 5. The radiator surface area depends on the stabilised LED power and on the applied Peltier element.

3.2. Control unit

3.2.1. Block diagram

A flow chart of the thermally stabilised LED LS control unit is given in Fig.2.

The control device consists of a current source supplying the LED, Peltier element power supply, temperature measurement unit and a control unit adjusting the Peltier element power supply parameters depending on the LED temperature.

The control device can be connected to a personal computer to implement additional algorithms for LS stabilisation. Besides, when connecting to the

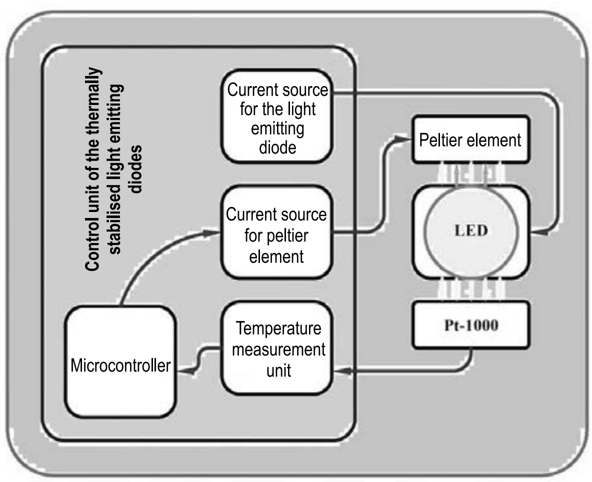

Fig.2. Flow chart of the LS control device

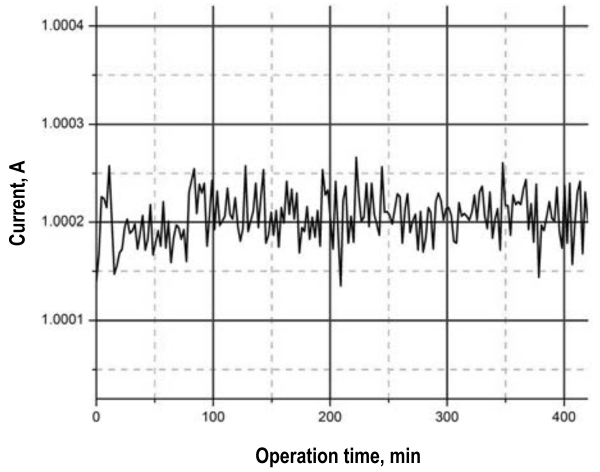

Fig.3. Stability of the current source supplying the LED

personal computer, a program control is possible for the LED power supply, Peltier element power supply and temperature measurement unit using a Pt-1000 type detector.

3.2.2. Main parameters

The current source for the LED supply is a stabilised source with discreteness of current adjustment of 30 x 10^{-6} A. The stability of the current source is 10^{-4} A for 10 hours of continuous operation. The accuracy of the current adjustment is equal to 10^{-4} A. Discreteness of the Peltier element power supply current adjustment is 50 x 10^{-6} A. The little pitch of the Peltier element current adjustment provides a high-precision stabilisation of LED temperature even at a slight change in ambient temperature. Discreteness of the temperature measurement by means of a thermal resistor is 0.01 °C.

The control device generates control signals for the Peltier element power supply based on the LED temperature change data.

The stability of the LED power supply current source was determined by means of voltage difference measurement on the external shunt resistor. To measure voltage, a 3458A *Agilent* voltmeter was selected. An electric resistor coil *P310* with a rated resistance of 0.1 Ohm was used as the shunt. To exclude the error associated with the shunt heating, its temperature was controlled in the measurement process. A stability diagram of the current source for the LED power supply is given in Fig. 3. It can be seen from the diagram that deviation from the current average value is ± 0.01 %, and instability during seven hours of operation is less than 0.005 %. LED temperature stability using the described control device is ± 0.01 °C at room temperature of 22 ± 2 °C.

4. STUDY OF THE PHOTOMETRIC PARAMETERS OF THERMALLY STABILISED LEDS USING POWER SUPPLY BY MEANS OF A SPECIALLY DEVELOPED CONTROL DEVICE

This article describes studies of photometric parameters of a LED LS with the first type of structure (with the tube of polytetrafluorethylene and matte glass).

Reaching an operation mode, including time for temperature stabilisation is no more than 0.5 h. A diagram of the LED reaching the operation mode with rated current of 1 A and stabilisation temperature of 36 °C is presented in Fig. 4. Stability of the

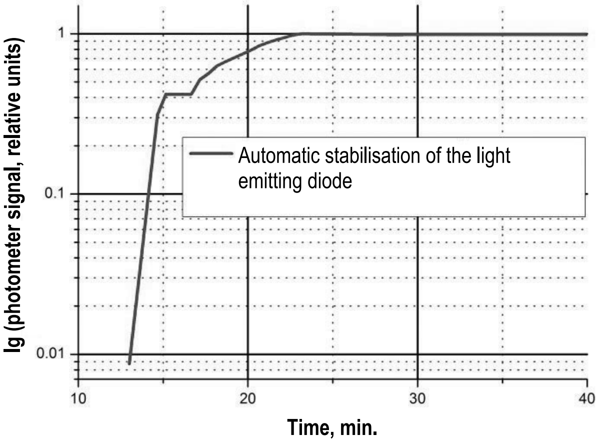

Fig.4. LS during operating mode

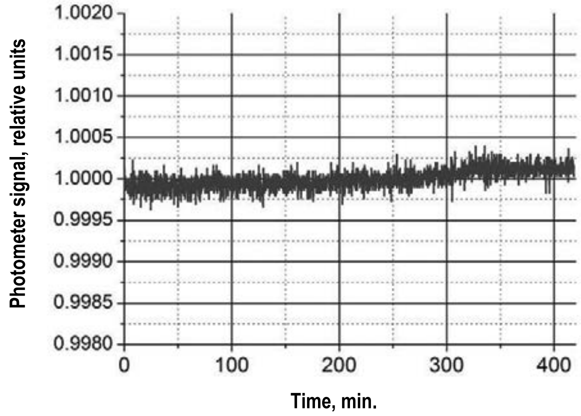

Fig.5 LS luminous intensity stability for 7 hours of continuous operation

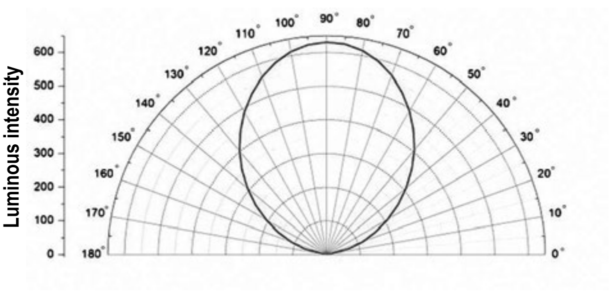

Fig.6. LS luminous intensity spatial distribution

LS luminous intensity is given in Fig. 5. It is equal to ±0.02 % for 7 h of LS continuous operation.

Luminous intensity reproducibility is less than 0.02 % for more than 30 cycles of switching-on and re-alignment. Luminous intensity of the specimens is 631cd [7].

Luminous flux stability and reproducibility is similar to the luminous intensity stability and reproducibility as luminous flux unit is transmitted by goniophotometric method [7–9]. This specimen luminous flux value is 1500 lm.

Fig. 6 shows the spatial distribution of luminous intensity, which allows drawing a conclusion that LS solid light distribution is uniform, because it is provided by a plastic tube and matte glass insert. The non-uniformity of luminous intensity in various meridian planes for azimuthal angles within an interval of ±70° relative to the LS photometric axis is no more than 2 %.

Fig. 7 shows dependences of LS colour co-ordinates on the angle of observation. The change in colour co-ordinates depending on the observation angle is $\Delta x = 0.006$ and $\Delta y = 0.005$, which is evidence of a high spectral uniformity of LS solid light distribution. LS spectral uniformity allows minimising the error connected with inaccuracy of the photometer correction according to the visibility curve of the human eye. LS correlated colour temperature is 3500 K.

5. CONCLUSION

In this article, standard thermally stabilised LSs based on powerful LEDs are presented, which were developed and studied at the VNIIOFI Federal State Unitary Enterprise. Their differential feature is a greater electric power of stabilised LEDs, which can reach 78 W, whereas power of other thermally stabilised LEDs was no more than 5 W [5, 6]. During the research, specimens were developed and

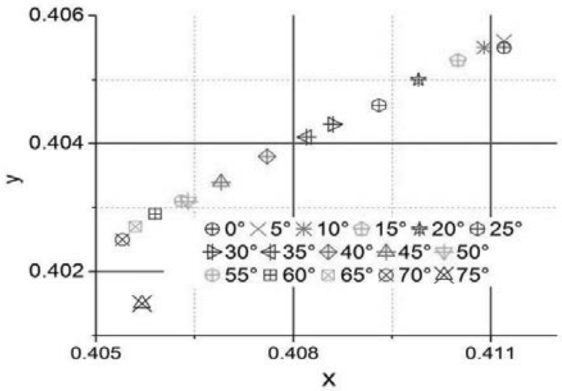

Fig.7. LS colour co-ordinate dependence on the observation angle

studied with luminous fluxes from 10 to 2500 lm. The study's results have show high stability and reproducibility of the new LSs. In future, introduction of these LSs in the Measuring instrument state register is planned in order to use them for verification and calibration of the photometric systems used for measuring parameters of LEDs and products based on these.

The work is performed using equipment of the Centre of Collective Use of High-Precision Measuring Technologies in the Photonics Field (ckp.vniiofi.ru) established on the VNIIOFI Federal State Unitary Enterprise basis and supported by the Ministry of Education and Science of the Russian Federation within Agreement #14.595.21.0003 of 8/28/2017 (unique identifier RFMEFI59517X0003).

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ANALYSIS OF LED DRIVER TOPOLOGIES WITH RESPECT TO POWER FACTOR AND THD

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ABSTRACT

Light Emitting Diodes (LEDs) are fast replacing incandescent lamps and CFLs in most of the developing nations. The reason can be attributed mainly to the enhanced lifetime and less energy consumption as compared to the other mentioned types. However one important aspect needs attention, the impact of driver on LEDs. LEDs are current controlled devices and hence emit maximum light with increase in current input to the device. This feature, boost up the light output but it increases the junction temperature of the device. Hence additional heat sinks are required to vent out the excessive heat generated due to increase current input to the LEDs. Those additional heat sinks are at times difficult to accommodate. So, designers have made arrangements to vent out the heat from the device. This is achieved by designing fins. However this arrangement is not suitable in places where the ambient temperature is more than normal. Thus, design of LED driver with controlled current input is essential in order to maintain the thermal limit of the device. Secondly, the AC-DC LEDs driver circuits, which are available in the market, are seldom equipped with input power factor and THD improvement circuitry as prescribed in IEC61000–3–2. This is essential for maintaining the energy efficiency of the nearest utility services and in addition also improves on the current drawn by the device. The following work envisages these issues and proposes corrective driver circuit based on two different driver topologies, buck-boost topology and flyback topology. Both these topologies are proposed in order to address the aspects of power quality and its impact on the life of the device. The simulation were done using *Green Point* simulation tool from *On Semiconductors*.

Keywords: driver, junction temperature, AC-DC converter, power factor, total harmonics distortion (THD)

1. INTRODUCTION

Liu and Yang in 2009 demonstrated different driver topologies for LEDs. The work was aimed at improved performance of the device by choosing proper driver topology. In fact it defined the inherent aspect of compatibility issues of LED driver circuits with respect to the device characteristics [1].

In the year 2010 a LED driver with buck boost topology and inherent power factor correction was proposed by Aguilar. The significant aspect of the driver circuit was it was able to improve the input power factor to close to unity. The biggest disadvantages of this topology are: (a) the LED drive current is modulated at twice the utility frequency and (b) in the discontinuous mode of operation (DCM) the operation increases component stress levels thus affecting the life of the device [2,3].

In 2011, a non-isolated buck converter with power factor correction was investigated to overcome the shortcomings of the earlier proposed circuit both for continuous current and discontinuous

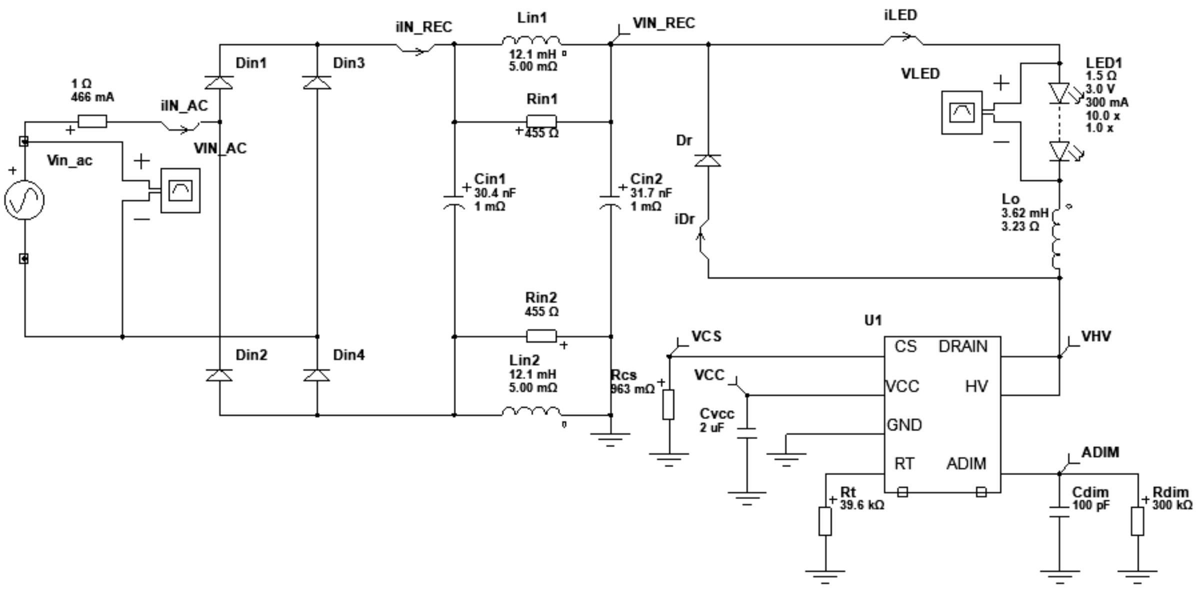

Fig.1. Proposed design of Buck Boost LED Driver using IC FLS0116

current mode of operation. In fact the proposed driver was designed for constant current drive with improved power factor. However it also increased the switching stress thus affecting the life of the LED lighting system [4].

The work done by Hu, Huber and Jovanovic in 2012 on a single-stage flyback power factor correction (PFC) circuit with a variable boost inductance for high brightness LED applications for the universal input voltage 90V-270V addressed the limitations of the conventional single-stage PFC flyback with a constant boost inductance. According to the proposed method the IEC61000–3–2 class C and corresponding Japanese standard JIS C61000–3–2 class C line-current harmonic limits were satisfied [5].

Further to this paper, the work done by Bhim Singh in 2012 deals with the PFC improved power quality based LED lamp driver. The proposed driver consists of a PFC Cuk DC-DC converter, which operates in continuous conduction mode (CCM) to improve the power quality at input AC mains [6].

In 2013 Cheng et. al. [7] has proposed a single-stage LED driver with interleaving PFC circuit for street-lighting applications. The circuit integrates an interleaved boost PFC converter with a half-bridge-type resonant converter into a single-stage converter. The presented AC-DC resonant converter uses interleaving methods to achieve input-current shaping, and possesses soft-switching functions on two active power switches to reduce their switching losses in order to increase the circuit efficiency. The proposed LED driver features low levels of input-current ripple, reduced switching losses, high power factor, low total harmonics distortion (THD) of input current and reduced components [7].

In 2014 the work done by researchers investigated the harmonics generated from LED driver and means to mitigate it. A low pass filter is proposed to suppress the harmonics complying with the prescribed standards. Again a work done by Sreemallika in 2014 on a comparative analysis of the AC-DC Converter topologies with Active Power Factor Correction for LED applications is presented by Jettanasen and Pothisarn in 2014.

The present work emphasizes on the aspects of power factor and THD analysis in two different driver topologies: buck boost and flyback driver circuit. The proposed circuit offers a comparative study for the two different topologies for LED driver. The output waveform for both the topologies offers an insight to the life of the device. The driver circuit emphasizes on controlling the T-point temperature and controlling the current delivered to the LEDs.

1.1. Proposed driver circuit

The existing LED drivers are basically boost converter, which drives the LED with a higher voltage than specified. It is understood that the light

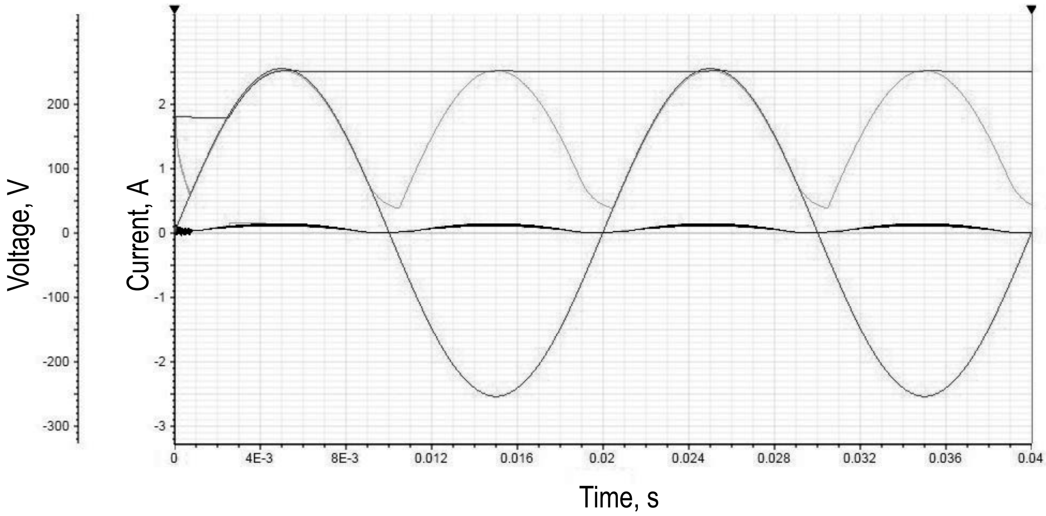

Fig.2. Input waveform of the buck boost driver

output of the LEDs is related to the current delivered to the device. In order to increase the light output, some of them drive in more current into the device thereby resulting in rise in junction temperature and, ultimately, in device failure [8–13].

The proposed design for Buck Boost converter LED driver is shown in Fig.1. The basic objective of this design is to maintain a steady output current to drive the LEDs without affecting the lifetime [8–10]. The buck boost driver has been designed without isolation from mains. This has been done because electrical insulation reduces thermal dissipation. Moreover, since heat sink is not electrically grounded, so chances of EMI generation cannot be ruled out. Further, as the electrical components are not mounted directly on the heat sink, hence the driver may be used in a non-isolated mode. The switching frequency is 50 kHz. The simulation is done through *Websim, Green Point, On Semiconductor.*

1.2. Start-up Analysis

In the successive start up analysis the input and output waveforms are observed in Fig.2 and Fig. 3 respectively. As evident from Fig.3, the output voltage varies between 16.5 V to 27.70V against the input voltage of 90V and 270V respectively. Further, from Fig.3 it is also understandable that the current varies between 0.6A to 0.8A at the input voltage of 90V and 270V respectively. The input power factor and THD analysis for the same cases are tabulated also. As observed from Table I it complies with the prescribed standards [11]. The efficiency of the dri-

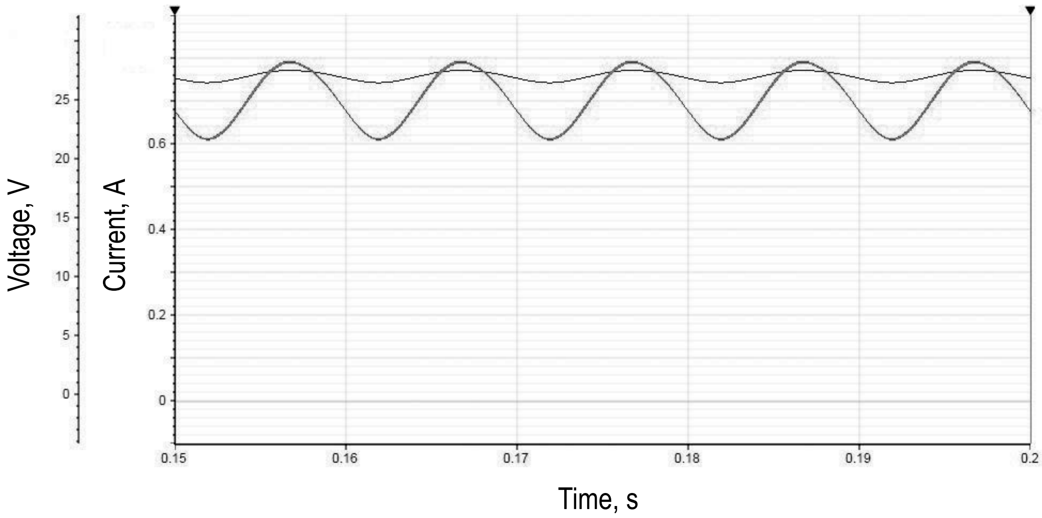

Fig.3. Output waveform of the LED buck boost driver

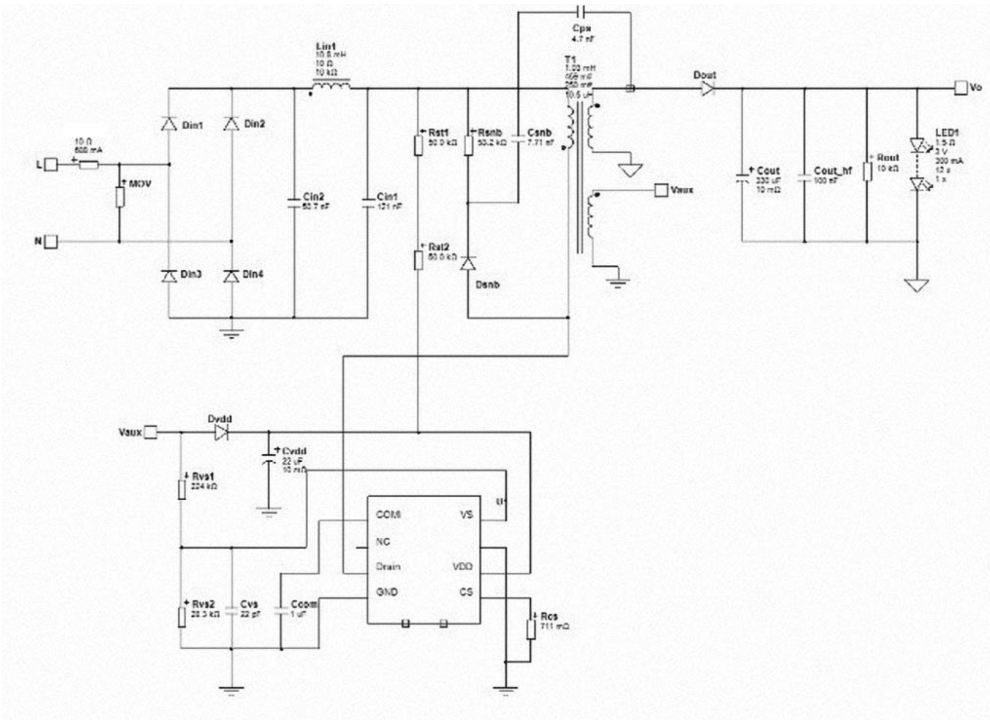

Fig.4. Proposed Flyback LED driver circuit with NCL30000

ver circuit is 84.81 %. The maximum and minimum THD_I and power factor are presented in Table I against the variable input of 90V and 270V.

1.3. LED driver- flyback topology

In the subsequent discussion the aspect Flyback type of LED driver is also simulated and analysed, Fig.4. The flyback is chosen to improve the power factor and THD within the limits as prescribed by the standards [11]. Moreover, it also aims to improve the efficiency of the system for the range of input voltage level, 90V – 270V. The THD analysis for the range of operating volatge is shown in Table 2, Figs.5,6. As observed, the power factor at 90V is 0.998 both for low and high output. The power factor at 270V is 0.993 and 0.992 for low and high output respectively. The minimum THD_I at 90V is 6.38 % at 90V and 12.13 % at 270V. Again, the maximum THD_I is 6.9 % and 12.55 % for 90V and 270V respectively. The switching frequency is 31.6kHz. The efficiency of the driver circuit is 86.7 %.

It is observed from Table 2 that the THD content for the proposed driver and the total harmonic content is within the presribed limits as suggested in IEC-61000–3–2 and the power factor is close to unity to be equal 0.93. This is implicative that

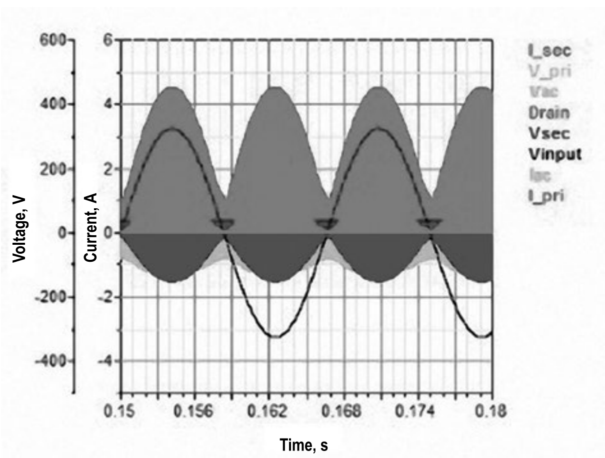

Fig.5.Input waveform of the LED flyback driver

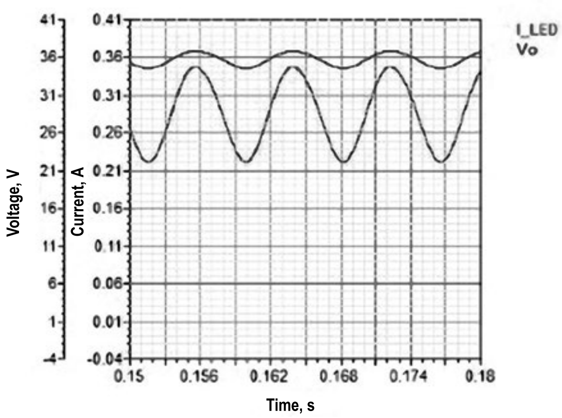

Fig.6. Output waveform of the LED flyback driver

Table 1. Power factor and THD analysis for the buck boost driver

Power Factor and THD	90V	270V
Power Factor at low Output	0.928	0.933
Power Factor at High Output	0.930	0.912
$THD_{I(Min)}$ LEDs with full driving current	7.38 %	10.13 %
$THD_{I(Max)}$ LEDs with full driving current	5.9 %	11.57 %

Table 2. THD analysis of flyback LED driver

Power Factor and THD	90V	270V
Power Factor at low Output	0.998	0.993
Power Factor at High Output	0.998	0.992
$THD_{I(Min)}$ LEDs with full driving current	6.38 %	12.13 %
$THD_{I(Max)}$ LEDs with full driving current	6.9 %	12.55 %

the current drawn by the device is not indicative of any damage to the junction temperature of the device [15–17].

2. CONCLUSION

From the above set of obtained simulation results it can be inferred that the short comings of the earlier design is addressed to an large extent and the driver circuit is capable of delivering power at constant current and constant voltage in the proposed buck boost driver circuit. Similarly the output current in the flyback topology is almost constant with 5 % peak to peak ripple. In addition to these the maximum and minimum T-point temperature for both the driver circuit is 40 °C and 55 °C. This protects the device from excessive rise in junction temperature and, thus, the life of the LEDs is prolonged. Moreover, the THD and harmonic content of the proposed circuit is also addressed and within the prescribed limits as per the standards [11]. With improvement in the input power factor the utility shall inject less reactive current into the system. The system efficiency is improved to a large extent and the use of LED shall not implicate the problems for a low power factor device.

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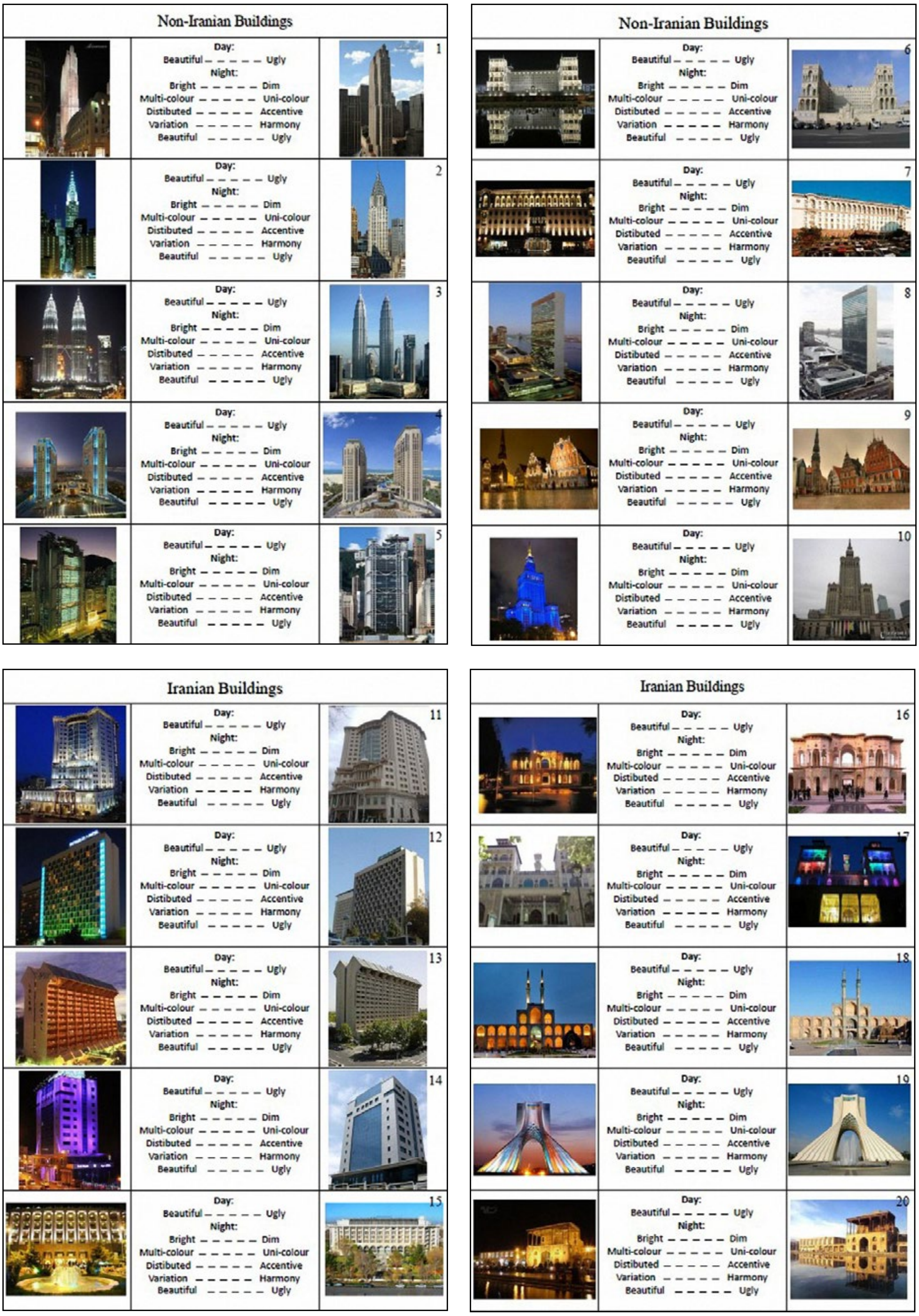

Fig. 3. The questionnaire

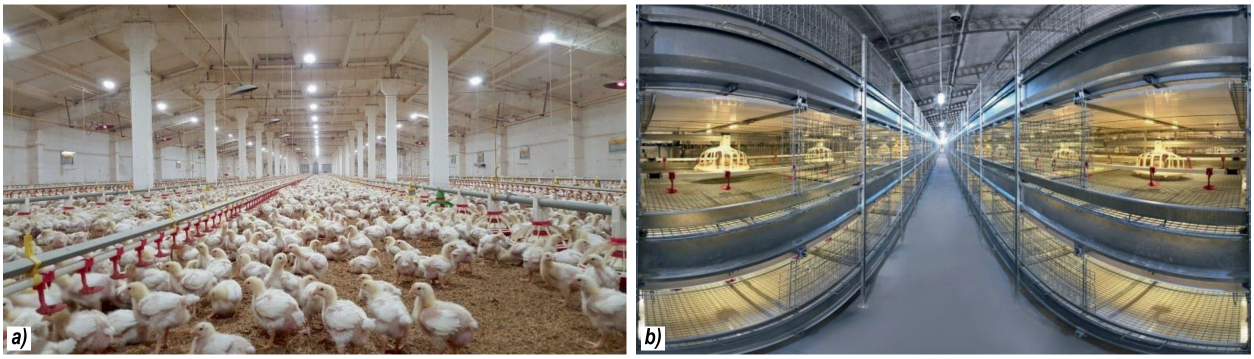

Fig. 4. LED lighting in poultry complex: a) with floor reared poultry [11]; b) with caged birds [12]

Fig. 7. Lighting in aqua farm using a submersible fixture [18]

Fig. 8. Oyster mushrooms farm [24]

Fig. 14. Multi-stack installation for growing plants with LED irradiation:
a) industrial, “*CityFarm*” type [33]; b) home-scale [34]

Fig. 13. Inter-row lighting system with *Philips LED-irradiators* [32]

Fig. 1. Temperature measurement of the LED without driver by using Thermal Imager (Fluke Ti 400) methodology adopted

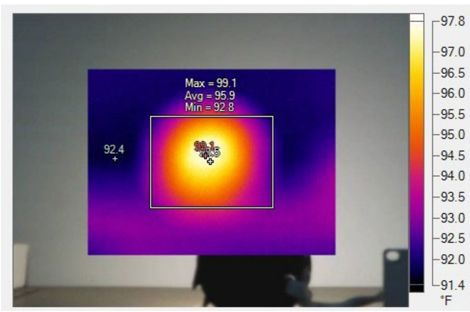

Fig. 2. Thermal image of COB type warm white LED at start-up time

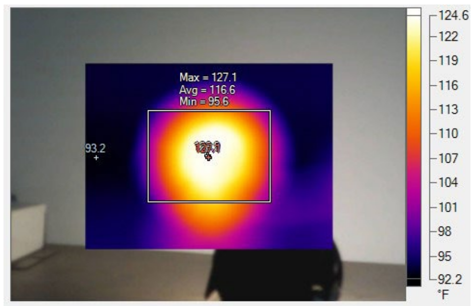

Fig. 3. Thermal image of COB type warm white LED after 60 min burning

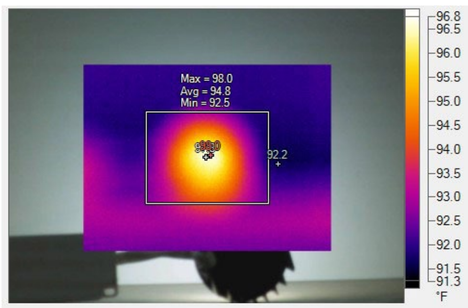

Fig. 4. Thermal image of COB type cool white LED at start-up time

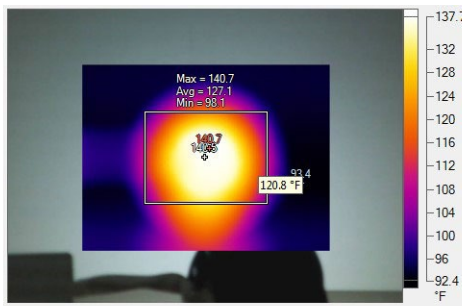

Fig. 5. Thermal image of COB type cool white LED after 60 min burning

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A SIMPLE METHOD TO IMPROVE VCP BY REDUCING DGR IN AN INTERIOR LIGHTING INSTALLATION

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ABSTRACT

Discomfort glare rating (DGR) and Unified glare rating (UGR) are main models currently used as discomfort glare evaluation systems, both of which are calculated employing four factors including the luminaire size, the luminaire position relative to the observer, background luminance, and the luminaires number and location. This study aims at proposing a simple solution for reducing DGR and thereby increasing visual comfort perception (VCP) in an interior lighting system. The proposed solution is based solely on variations of luminaire surface area without change in other factors, e.g. candlepower and number and location of luminaires in the lighting system. To this end, firstly, the equations related to DGR were modified for a desired luminaire, and, secondly, by solving the modified equations, the new luminaire surface area was obtained, which caused DGR decrease and VCP improvement. Finally, by some modifications in the location of selected luminaires having main role on DGR, the VCP rose considerably.

Keywords: DGR, VCP, Interior lighting, luminaire surface area

1. INTRODUCTION

Glare is a phenomenon known to the public; however, it is not easy to define in technical terms [1–4]. The Illuminating Engineering Society of North America (IESNA) defines glare as one of the two following conditions [5, 6]:

"1- Too much light; 2- Excessive contrast, i.e. the range of luminance in the field of view (FOV) is too great".

Although several measurement systems such as discomfort glare rating (DGR), unified glare rating (UGR), British glare index (BGI), Cornell glare index (CGI), predicted glare sensation vote (PGSV), discomfort glare probability (DGP), and visual comfort probability (VCP) have been developed, there is still need to validate the existing models or develop new reliable metrics [7–10].

To evaluate glare, light cannot be measured in lx or foot candles. Instead, it is luminance that has a great impact on glare, which typically is measured in candelas per square meter (cd m^{-2}) or nits in former time [6, 11, 12]. In practice, in a good lighting design either the light is diffusing within the space or the luminaire is enclosed or shielded from FOV to reduce the luminance [6, 13]. Reducing luminance results in DGR decline and subsequently VCP improvement [14]. The VCP value predicts the percentage of people who would be expected to find the lighting acceptable in terms of discomfort glare [13, 15]. Manufacturers provide VCP tables for most luminaires, which is specified for a person in a particular location looking horizontally in a specific direction. The room size, reflectance, fixture type and location, and the number of fixtures in FOV are all determining factors of VCP for interior lighting [5, 7, 10, 15–17].

In 1949, Luckiesh and Guth conducted a comprehensive study, which become the basis for the development of VCP index. They called the metric they developed in that study "borderline between comfort and discomfort" [18]. In 1963, Guth finally proposed a method for calculating DGR, after a decade of ongoing studies on discomfort glare, which was merged by the work of other scientists of this field and published by IESNA [19]. Despite many modifications and simplifications that have been carried out from 1963 to 2000, DGR and VCP still need to be improved [9, 20, 21]. The present study describes a method for VCP improvement by reducing DGR in interior lighting design only by changing the surface area of luminaires (the surface area of shielding of the light sources), without any modifications in the illuminations and arrangement of luminaires. To do this, a complete DGR calculation procedure for interior lighting design suggested by IESNA [1966–2000] and originally derived from Luchiesh and Guth's works, was employed [5]. The main objective of this study was to establish a direct relationship between index sensation (*M*) and luminaire surface area (*A*) for each luminaire so that by any changes in *A*, *M* and as a result DGR could be varied in a specific interior lighting installation. The paper will focus on mathematical procedures and discuss it in entire detail. The reason for choosing *A* is that making any change in the other variables leads to disruption in initial lighting design.

2. MATHEMATICAL PROCEDURES

The procedure outlined in this work for decreasing DGR in a room is essentially focused on the index sensation *M*, defined for one luminaire as below [5]:

$$M = \frac{L_s Q}{P F^{0.44}}, \tag{1}$$

where:

L_S is the average luminance of the glare source (laminaire) [cd/m^2],

Q is the function of visual size of the glare source,

P is the index of the position of the glare source with reference to the line of sight, which is calculated for any luminaire located in FOV,

F is the average luminance of the entire FOV [5, 15].

The average luminance, L_S, is calculated using the following equation [5]:

$$L_s = \frac{I}{A}, \tag{2}$$

where:

I *is* the luminous intensity [cd],

A is the luminaire surface area (shielding surface area) observed by the viewer,

P is also created from the Guth's experiment [22], which is given by the formula [5, 16]:

$$P = \exp[(35.2 - 0.31889\alpha - 1.22e^{-2\alpha/9})10^{-3}\beta + (21 + 0.26667\alpha^2)10^{-5}\beta^2], \tag{5}$$

where:

α is an angle from vertical line of the plain containing the luminaire and the line of sight shown in Fig. 1, β is an angle between the line of sight and the line from the observer to the luminaire (D) shown in Fig. 1,

Furthermore, both Q and F in Eq.1 are expressed in terms of solid angle subtended at the eye by each luminaire, ω_S, which are calculated as below [5, 7, 21, 23]:

$$Q = 20.4\omega_s + 1.52\omega_s^{0.2} - 0.075, \tag{4}$$

$$F = \frac{1}{5}[L_w\omega_w + L_f\omega_f + L_c(\omega_c - \sum_{i=1}^{N}\omega_s) + \sum_{i=1}^{N} L_s\omega_s], \tag{5}$$

where:

L_w is wall cavity luminance, L_f is floor cavity luminance, L_c is ceiling cavity luminance, ω_c is the solid angle subtended by ceiling.

Also, the solid angle subtended by each luminaire is equal to [5]:

$$A = \frac{\omega_s}{(V / D^3)}, \tag{6}$$

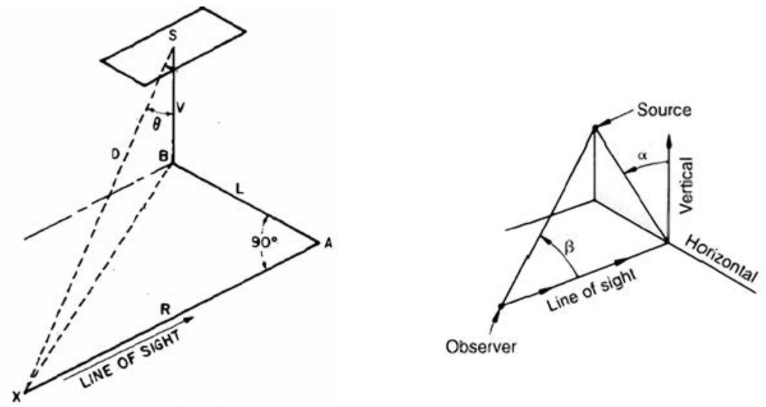

Fig.1. Geometric positions of the observer and luminaire as used in VCP calculations with courtesy of IESNA [1966 & 2000]

where:

V is the direct distance from observation point to centre of luminous area, *D* is the direct distance from observation point to photometric angle from nadir (shown in Fig.1.).

The Discomfort Glare Rating, *DGR*, is after all defined as [5, 7, 8]:

$$DGR = (\sum_{i=1}^{N} M_i)^{N^{-0.0914}}, \quad (7)$$

where;

M is the sensation index, *N* is the number of luminaires in the FOV.

The first issue is to determine how *M* varies with ω_s (or *A*). If we consider that the interior lighting system has only one luminaire, *e.g.* Luminaire No.1 in Guth's experiment [22] and putting the values *Ls*=138 and *P*=1.62 into the Eq.1, the sensation index of the luminaire No.1 (M_1) can be calculated as [5, 7, 24]:

$$M_1 = \frac{138(20.4\omega_s + 1.52\omega_s^{0.2} - 0.075)}{1.62 \times \frac{1}{5}[52.8 + 85.8 + 38.35(1.496 - \omega_s) + 138\omega_s)]}. \quad (8)$$

Plot of M_1 versus ω_s is shown in Fig. 2. As can be seen from Fig. 2, *M1* is an ascending function when $\boldsymbol{\omega_s} > 0$, meaning that it also rises with the luminaire surface area (shielding surface area), *A*, which is proportional to its ω_s. Likewise, the decrease of *A* will lessen the amount of *M*, and consequently results in a DGR decline. On the other hand, the decrease of *A* causes an increase of the glare source luminance (according to Eq. 2), leading to *M* rising otherwise. To overcome this inconsistency, all of the photometric characteristics of luminaires especially the intensity of luminaire should remain unchanged, excepting *A*, as has been emphasized in this study. Therefore, for two conditions specified as OLD and NEW, representing before and after applying modifications in the lighting system, the Eq. 2 can be rewritten under the assumption that the light intensities of all luminaires are equal:

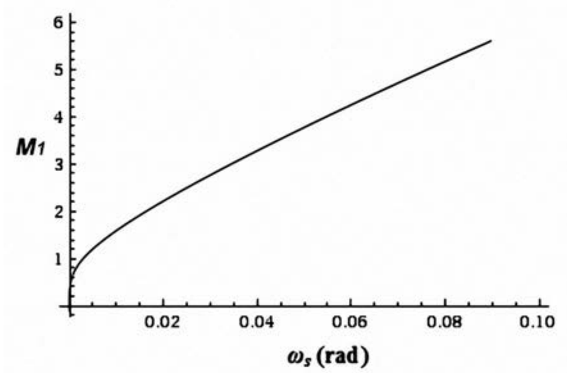

Fig.2. The variation of index sensation M_1 with respect to the solid angle subtended by luminaire No.1 in Guth's experiment, based on Eq.8

$$L_{sOLD} A_{OLD} = L_{sNEW} A_{NEW}. \quad (9)$$

Substituting ω_s with *A* in the Eq. 9, it will be converted to:

$$L_{sNEW} = L_{sOLD} \frac{\omega_{s\ OLD}}{\omega_{s\ NEW}} \quad (10)$$

In our proposed method, in order to modify the old sensation index M_{iOLD} and getting a new value M_{iNEW} where $M_{iNEW} < M_{iOLD}$, in which *i* indicates the i^{th} luminaire, the Eq. 8 is rewritten as follows Eq. 11, which can be seen below.

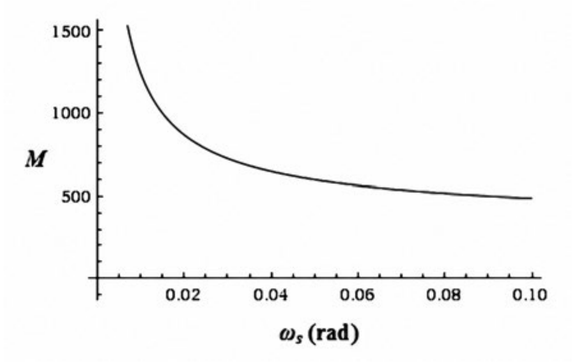

Fig. 3. The variation of new index sensation $M_{i\ NEW}$ with respect to the new solid angle subtended by each luminaire after modification

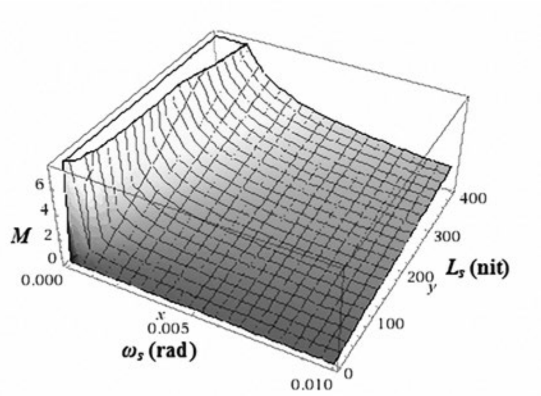

Fig.4. Index sensation (z) variation against the luminance (y) and the solid angle (x) subtended by each luminaire

By putting Eq.10 into Eq.11 it yields to Eq. 12 presented below.

Taking into consideration the new calculations, plotting $M_{i\ NEW}$ versus $\omega_{si\ NEW}$, again for luminaire No.1 in Guth's experiment, leads to a descending function for M when $\omega_{si\ NEW} > 0$ as depicted in Fig. 3.

Due to high values of L_s as compared to other factors in Eq.1, L_s value has a great impact on the M amount. Therefore, considering both variables of M i.e. L_s and ω_s, a three dimensional diagram can be plotted for M against ω_s and L_s as shown in Fig.4.

As it is clearly seen in Fig. 4, M increases with L_S growing and ω_S (or A) decline.

2.1. THE FORMULA FOR CALCULATING NEW *DGR*

If Eq. 12 is applied for all luminaires, then the sum of obtained M_{iNEW} can be replaced in Eq. 7 and the new DGR will become:

$$DGR_{NEW} = = (M_{total\,OLD} - \sum_{i=1}^{n} M_{i\,OLD} + \sum_{i=1}^{n} M_{i\,NEW})^{N^{-0.0914}}, \quad (13)$$

where:

$M_{total\ OLD}$ = the total sensation index of luminaires in the FOV before modification,

N = the number of luminaires in the FOV,

n = the number of luminaires whose surface areas were modified.

Once the DGR_{NEW} has been calculated, the VCP_{NEW} can be determined either by using a conversion chart or a mathematical relationship. In the present study the lighting measurements conducted by IESNA handbook [1966–2000] have been employed thanks to the evaluation of sensation index M by several computational procedures and its description in detail step by step.

3. RESULTS AND DISCUSSION

Guth (1966) proposed a VCP computing model which has been the reference for all editions of IESNA handbook[5, 22]. In the present study, the Guth's model was used to obtain the lighting data. The lighting layout determined by Guth was symmetrical with respect to the line of sight and includes 64 luminaires 54 of which are in the FOV[22]. Our modification for DGR has been started with selecting luminaires whose index sensa-

$$M_{i\,NEW} = \frac{L_{s\,NEW}\,(20.4\,\omega_{s_{i\,NEW}} + 1.52\,\omega_{s_{i\,NEW}}^{0.2} - 0.075)}{P\{\frac{1}{5}\times[L_w\omega_w + L_f\,\omega_f + L_c\,(\omega_c - (\omega_{s_{i\,NEW}} + \sum_{i=1}^{N-1}\omega_{s_i})) + (L_s\omega_{s_{i\,NEW}} + \sum_{i=1}^{N-1} L_{s_i}\,\omega_{s_i})]\}^{0.44}}. \quad (11)$$

$$M_{i\,NEW} = \frac{L_{si_{\ OLD}}\ \omega_{si\ OLD}\,(20.4\,\omega_{s_{i\,NEW}} + 1.52\,\omega_{s_{i\,NEW}}^{0.2} - 0.075)}{P\,\omega_{si_{\ NEW}}\,\{\frac{1}{5}\times[L_w\omega_w + L_f\,\omega_f + L_c\,(\omega_c - (\omega_{s_{i\,NEW}} + \sum_{i=1}^{N-1}\omega_{s_i})) + (L_s\omega_{s_{i\,NEW}} + \sum_{i=1}^{N-1} L_{s_i}\,\omega_{s_i})]\}^{0.44}}. \quad (12)$$

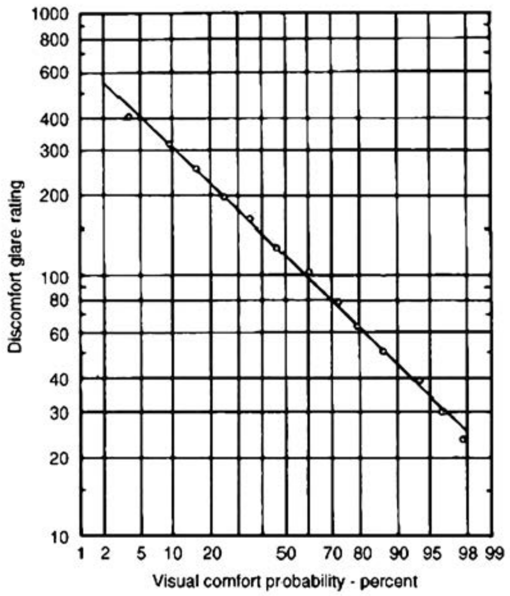

Fig. 5. The conversion chart to obtain *VCP* having *DGR*

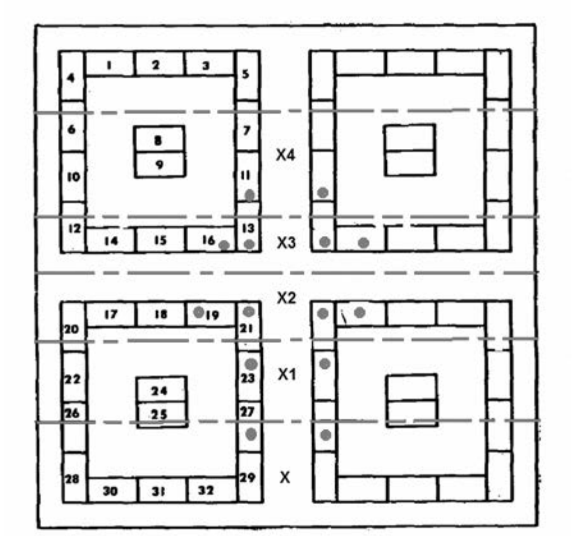

Fig. 6. The lighting layout with 54 luminaires in an interior lighting system: the fourteen modified luminaires, marked with circles and the x, x1, x2, x3 and x4 are positions of four observers, with courtesy of IESNA [1966]

tions *M* are higher comparing to the average of $\overline{M}$ among 54 luminaires and then reducing the values of the sensation index of these selected luminaires by 20 % as M_{NEW} = 80 %M_{OLD}. Table 1 shows the selected luminaires with their overall main characteristics. It is obvious from Table 1 that seven luminaires have the sensation index values greater than $\overline{M}$. The new subtended solid angles, ω_{siNEW}, were calculated for these seven selected luminaires by putting M_{NEW} values in the Eq.12.

The lighting data, L_s, *P*, and L_ω, were replaced in the equation represented in Table 1 and then ω_{siNEW} amounts were obtained. It should be noted that the terms $\sum_{i=1}^{N-1}\omega_s$ and $\sum_{i=1}^{N-1} L_s\omega_s$ in all equations in Table 1 are the summations of ω_s and $L_s\omega_s$ for all luminaires in the interior lighting system, except for luminaire i^{th} with the subtended solid angle ω_{siNEW}. Having ω_{siNEW}, the new luminaire surface areas, $A_{i\,NEW}$ can be calculated as below [5, 24]:

$$A_{i\,NEW} = \frac{\omega_{si\,NEW}}{(V/D^3)}, \qquad (14)$$

where:

V and *D* are shown in Fig.1.

The corresponding results are shown in Table 2. It is seen from the Table 2 that the increase of luminaire surface areas is not proportional to their distances from observer (*D*) resulting from the simultaneous reduction of *M* amounts to ca. 50 % of the initial values.

3.1. CALCULATION OF NEW *DGR*

Once $\sum_{j=1}^{7} M_{OLD}$ and $\sum_{j=1}^{7} M_{NEW}$ for seven luminaires in Table 2 were calculated, the total M_{NEW} was determined as 289.4 and then the new *DGR* was obtained for 54 luminaires applying Eq. 13 as follows:

$$DGR_{NEW} = (382.8 - 186.8 + (186.8/2))^{54^{-0.0914}} = 49.18$$

Finally, VCP_{NEW} was obtained about 88 using the conversion chart, as depicted in Fig.5.

The main results for M_{total}, *DGR* and *VCP* before and after modification in the interior lighting system reported by Guth are shown in Table 3. The *VCP* improvement can be clearly seen from this table.

3.2 NEW DGR AND DIFFERENT OBSERVATION POINTS

The main objective of the present work was to develop a simple method to decrease *DGR*, and thereby improve *VCP* in a specific interior lighting installation by solely increasing surface area of

Table 1. The selected luminaires and the values of Eq. 12 parameters for each selected luminaire

N0.	L_{si} OLD	M_{i-} OLD	M_{inew}	P	$\sum_{i=1}^{N-1}\omega_s$	$\sum_{i=1}^{N-1}L_s\omega_s$	ω_{siNEW} formula $L_{si\,OLD}\times\omega_{si\,OLD}(20.4\times\omega_{sNEW}+1.52\times\times\omega_{sNEW}^{0.2}-0.075)=M_{iNEW}\times\omega_{si\,NEW}\times\times P\times(A\times\omega_{sNEW}+B)^{0.44}$
1	158	7.3	3.65	1.95	0.378	130.71	$158\times0.0050(20.4\times\omega_{s1NEW}+1.52\times\times\omega_{s1NEW}^{0.2}-0.075)=7.11\times\omega_{s1NEW}(23.93\times\times\omega_{s1NEW}+62.36)^{0.44}$
2	178	7.8	3.9	1.69	0.385	130.98	$178\times0.00292(20.4\times\omega_{s2NEW}+1.52\times\times\omega_{s2NEW}^{0.2}-0.075)=6.59\times\omega_{s2NEW}(27.93\times\times\omega_{s2NEW}+62.41)^{0.44}$
3	168	8.0	4.0	2.72	0.376	129.47	$168\times0.0121(20.4\times\omega_{s3NEW}+1.52\times\times\omega_{s3NEW}^{0.2}-0.075)=10.88\times\omega_{s3NEW}\ 23.93\times\times\omega_{s3NEW}+62.36)^{0.44}$
4	195	9.2	4.6	1.87	0.383	130.57	$195\times0.00479(20.4\times\omega_{s4NEW}+1.52\times\times\omega_{s4NEW}^{0.2}-0.075)=8.60\times\omega_{s4NEW}(23.93\times\times\omega_{s4NEW}+62.36)^{0.44}$
5	673	15.7	7.85	8.50	0.360	112.99	$673\times0.0275(20.4\times\omega_{s5NEW}+1.52\times\times\omega_{s5NEW}^{0.2}-0.075)=66.72\times\omega_{s5NEW}\ 23.93\times\times\omega_{s5NEW}+62.36)^{0.44}$
6	326	18.0	9.0	2.81	0.370	125.80	$326\times0.0175(20.4\times\omega_{s6NEW}+1.52\times\times\omega_{s6NEW}^{0.2}-0.075)=25.29\times\omega_{s6NEW}\ 23.93\times\times\omega_{s6NEW}+62.36)^{0.44}$
7	500	27.4	13.7	4.55	0.348	111.50	$500\times0.0400(20.4\times\omega_{s7NEW}+1.52\times\times\omega_{s7NEW}^{0.2}-0.075)=62.33\times\omega_{s7NEW}\ 23.93\times\times\omega_{s7NEW}+62.36)^{0.44}$

some luminaires. In the cases where the ceiling can always be seen by the viewer in one direction, this simple method could be used appropriately to decrease *DGR* by only increasing the surface area of the luminaires having the most *M* among the others. In practice, it seems that the simplest way to reduce M_{total}, is to increase the surface area of luminaires installed on the ceiling without changing other properties of the lighting system like light intensity. In the present work, applying the mentioned modifications to the 14 selected luminaires, the total surface area increased by 57.64 ft^2 (an increase of 15 % for the whole luminaires) leading to the decline of M_{total} by 24 %. Subsequently, the *DGR* decreased by 19.3 % and then *VCP* improved by 8.6 %. These findings are true for an observation point which covers the 84 % of luminaires ((54/64)×100=84 %). However, such a reduction in *DGR* for observation points that cover less than 84 % of luminaires will be obtained by changing the surface area of fewer luminaires and inversely for observation points that cover more than 84 % of luminaires will be achieved by bringing more luminaires into account.

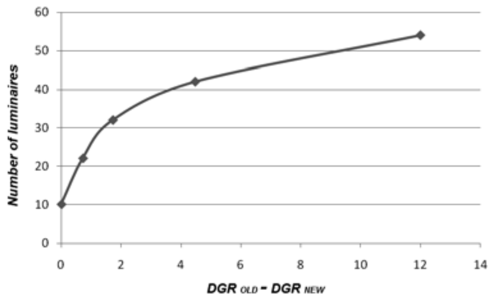

Fig. 7. Plot of $\Delta = DGR_{OLD} - DGR_{NEW}$ versus the numbers of luminaires in the observer's FOV, based on Fig.6

Considering X, X1, X2, X3 and X4 as different observation points as depicted in Fig.6, all of the determinant factors before and after modifying the luminaires surface area including M_{OLD}, DGR_{OLD} and VCP_{OLD} and also M_{NEW}, DGR_{NEW} and VCP_{NEW} were calculated for each observation point. The results are shown in Table 4. It should be noted that it was

Table 2. Calculated luminaire surface area for selected luminaires before and after modification

i	ω_{iOLD}	ω_{iNEW}	V/D^3	A_{iOLD}	A_{iNEW}
1	0.000500	0.00710	0.000567	7.50	12.52
2	0.000222	0.00411	0.000387	7.50	10.62
3	0.012100	0.01880	0.001610	7.50	11.67
4	0.004790	0.00690	0.000639	7.50	10.80
5	0.027500	0.04760	0.009770	2.81	4.87
6	0.017500	0.02850	0.002380	7.50	11.97
7	0.040000	0.07560	0.005330	7.50	14.18

Table 3. Comparison of M_{total}, *DGR* and *VCP* values before and after modification in the interior lighting system

	OLD (before modification)	**NEW (after modification)**
M_{total}	382.8	289.4
DGR	62	50
VCP	81	88

Table 4. Variation of M_{total}, *DGR* and *VCP* values for the different positions of an observer

	Observation point	**Number of luminaires in the FOV(*N*)**	M_{total}	***DGR***	***VCP***
OLD (before modification)	X	54	382.8	62	81
	X1	42	266	52.68	87
	X2	32	185	44.72	91
	X3	22	120.2	36.82	94
	X4	10	**50.4**	**23.93**	100
NEW (after modification)	X	54	289.4	50	88
	X1	42	234.8	48.21	88.5
	X2	32	175.28	43	92
	X3	22	117	36.10	94.5
	X4	10	**50.4**	**23.93**	100

not require to modify any luminaire for X4, and as a result, the values before and after luminaire modifications are the same for that point.

According to the Table 4, the *DGR* values are less for observation points that cover fewer luminaires. These findings show that the more the presence of bright luminaires happens in the FOV (*N*), the more *DGR* occurs. The difference between DGR_{OLD} and DGR_{NEW} ($DGR_{OLD} - DGR_{NEW}$), which was denoted by Δ, indicated that for observation points x to x4, it varied proportionally with the number of luminaires in the FOV (*N*), as depicted in Fig.7.

These results show that if *DGR* is acceptable for an observer who observes all installed luminaires, then it will certainly be acceptable for other observers for whom fewer installed luminaires are present in the FOV. It should be noted that for the interior lighting luminaires, which have already been installed, it is difficult to decrease *DGR* via increasing of the surface area of each luminaires, because *DGR* is reliant on *M* which in turn is not only dependent on luminance of each luminaire but also on viewer's position in a complex form. However, for interior lighting designs which are pre-installed, it is generally feasible.

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NOCTURNAL ARCHITECTURE OF BUILDINGS: INTERACTION OF EXTERIOR LIGHTING AND VISUAL BEAUTY

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ABSTRACT

Exterior lighting of buildings and their appearance at night is an important issue in architectural design. While the effect of natural daylight on the appearance of a building during the day is not completely under the control of the designer, exterior lighting at night is a design choice that can strongly effects the beauty of a building. The current research Delft University of Technology examined the effect of exterior lighting on the appearance of buildings at night using a questionnaire-based research methodology accompanied by in-depth statistical analysis of the results. The aspects addressed are how exterior lighting and its elements, such as luminous intensity (low vs. high intensity), colour diversity (single vs. multiple colour), lighting type (accent vs. uniform), and lighting state (harmonized vs. diversified), can affect the perception of the beauty of a building facade at night. The results confirm that exterior lighting of buildings substantially increases the beauty of the facades at night. The beauty of buildings increases with the use of single-colour accent lights in harmony with the façade and as the light intensity increases. On the other hand, the use of multi-colour or uniform lights with low intensity or not in harmony with the façade negatively impacts the beauty of the buildings. The results also indicate that light intensity and lighting types affect the perception of beauty of building facades more than colour diversity and lighting conditions.

Keywords: lighting, nocturnal architecture, visual beauty

1. INTRODUCTION

Nocturnal architecture is a concept that a viewer perceives from an architecture at night [1, 2]. As the trend for urbanization and night life in major cities increases, the need to design beautiful and eye-catching exterior lighting of building facades increases [3, 4, 5, 6]. It is evident that the aesthetic atmosphere of cities differs from day to night [7]. Consequently, the presentation of facades, objects, sculptures, and green spaces at night is tightly coupled with the type of lighting. Exterior lighting of monuments and buildings in cities is often designed to add to their attractiveness and provide a distinct identity for them [4, 8].

Because the façade of a building is the site at which it exposed and connected to the outside world, it has an effect on the surrounding area as well as on the people living nearby. The design of the exterior lighting of a building should be considered to be as important as the design of the façade of the building itself. Attractive lighting can make a unique impression about a building in the eye of the viewer and turn a normal building into a tourist attraction. On the other hand, unattractive exterior lighting could turn a beautiful monument to an eyesore at night.

The present study examined the effect of natural and artificial lighting on perceptions about the beauty of a building. Does a building seem more beautiful during the day in natural light or during the night in artificial lighting? The study examine how and to what extent the elements of artificial lighting, light intensity, light colour, lighting method, and lighting mode, affect the perception of the beauty of the building.

The research methodology was based on field studies. A literature review on exterior lighting and its effect on the perception of beauty were first completed. A questionnaire was then designed based on the literature review to examine the effect of artificial and natural lighting on the appearance of buildings. The questionnaire was completed by groups of participants with different levels of visual literacy. The questionnaires offered photographs of the façades of a number of randomly selected buildings at night and in the day and participants were asked to rate the beauty of each building on a scale of 1 to 5. Participants were asked to rate the effect of different lighting elements on the appearance of the building. SPSS software is used to analyze the qualitative data. Semantic differentiation and bipolar adjectives were used to translate the qualitative data to quantitative values to evaluate the degree of influence of natural daylight and artificial exterior lighting on the perceived beauty of buildings and monuments.

Section 2 introduces light and its effect on human perception. Section 3 describes the research methodology and the design of the questionnaire. The analysis of the data is discussed in Section 4 and Section 5 presents the conclusions.

2. ROLE OF LIGHT IN HUMAN PERCEPTION

Light provides humans with perceptions of their surroundings. The effect of light cannot be touched, only perceived. Perceptions about an object in the mind derives from its appearance when exposed to light and individuals do not have exactly the same perception of one object [14].

Natural daylight creates the best perception of surroundings [8]. Sunlight can illuminate objects uniformly to make the light intensity on all surfaces be approximately the same. The effect is similar to the reflection of lighting from objects, which allows individuals to see them. Artificial lighting, on the other hand, can create different perceptions of an object. Artificial lighting could make part of an object seem more prominent than the other parts. The perception of that object when artificially lighted is likely different from the perception in natural daylight.

2.1. Aesthetics and effect of light on perception of beauty

The nature of lighting has both technical and artistic aspects. The artistic aspect of lighting plays a role in creating the perception of beauty. Aesthetics is a branch of philosophy that focuses on concepts such as beauty and ugliness. It is the ability to better understand objects and surroundings and can change perceptions about an object [12]. For centuries, philosophers and artists have looked at aesthetics as either natural or geometric (manmade). From the eighteenth century onward, philosophers have viewed aesthetics more from a psychological and individual perspective [18].

The aesthetic value of an object can be perceived when that object is exposed as an independent entity to the viewer and stimulates the viewer to perceive its beauty [17]. Light is a means for this and provides visual communication between the viewer and the surroundings [14]. It is light which makes objects visible to humans and enables them to perceive their environment and its elements. This is necessary to perceive the beauty of an object.

2.2. Interaction of colour and light

Similar to lighting, colours are significant in terms of aesthetics [20]. Colour is a component of visual perception that can stimulate emotional feelings [15]. The colour of light is one influence of lighting and can signify both white and coloured lights. Given the fact that lighting is a major factor in perception of surroundings, the colour of light can be used to influence this perception. The psychological effects of colour can change the conceptual specifications of an object and its elements to create relaxing and soothing conditions that accentuate beauty. The use of coloured light enables humans to see the modes and effects of objects and their elements without changing their structural forms [9].

2.3. Novel lighting technologies

Light is necessary when providing a visual perception of an environment to the observer. Lighting and architecture are inter-dependent. Light is like the spirit through which lighting design can make a building look alive [19]. Perception of the architecture of a building is often affected by light, whether natural or artificial. Light can enhance a state or feature of architecture to provide it a unique identity in the surrounding space. Light is a tool with which to express the architecture of a building. Lighting that an architect considers favourable for the building during the day and at night effects the atmosphere around the building and shapes the mental form of the building [7].

Lighting can serve to justify a space, a building, or an element. It can be an endorsing or attenuating factor for the architectural form of a building [2]. Lighting is usually deployed to add beauty and identity to urban spaces. Vertical panels of building facades create a sense of perception in city squares and streets. Lighting the facades at night can change the atmosphere of the cities and create attractive site-scenes.

The morphological and operational characteristics of a building affect the lighting design for that building. Monuments with complex architecture and detailed ornamentation should be lighted such that the contrast between shadow and bright light makes visible both small and large elements and clearly highlights the ornamentation. The power of the light source should not overshadow some parts (especially details) and obscure them.

2.4. Nocturnal architecture

Exterior lighting of building façade expresses nocturnal architecture of the building [2,3]. Just as the architecture and application of buildings differ, their lighting design also differs. The lighting design depends on the architectural style of a building and its visual characteristics. Each building has its own identity that can be expressed using proper lighting design. Proper lighting should also put the building into harmony with its surroundings.

Lighting of the façade of a building is affected by the type of façade (rigid or glass) and the way light is projected onto the façade. The form of a façade is determined by the type and form of the material used and by the direction and colour of the light projected onto it. During the day, a façade looks different because of the change in the angle of light as well as the change in the spectrum of the light. At different moments of day, an observer will form different perceptions of the facade of the same building. At night, the façade will appear to be very different from its appearance during the day. Emphasis on specific elements and parts of the façade and a change in the light colour, the elements of lighting design, changes the way the façade appears at night. There are three methods to consider when considering the type and detail of the façade in the design of lighting: uniform lighting of building surfaces, emphasis on indicating elements of buildings (accent lighting), and creating attractiveness and visual variety [13].

In uniform lighting different levels of a façade are lighted uniformly. These levels can be horizontal, vertical, inclined, curved, or convex (e.g., domes). The level chosen for uniform lighting depends on the architecture and application of the building and its surroundings. Facades that are uniformly lighted without differences in contrast at different levels seem flat and two-dimensional. To create such uniform lighting, the light must be projected from a distance with a wide angle. Such lighting makes the entire façade of the building vi-

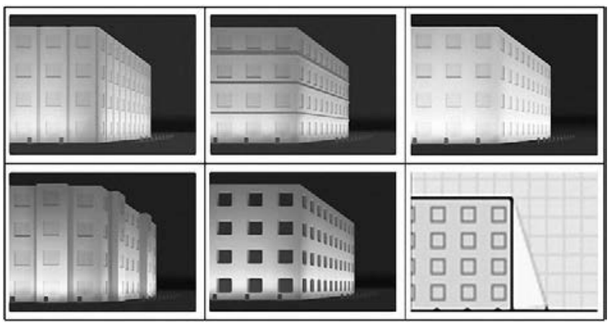

Fig. 1. Uniform lighting of facades [21]

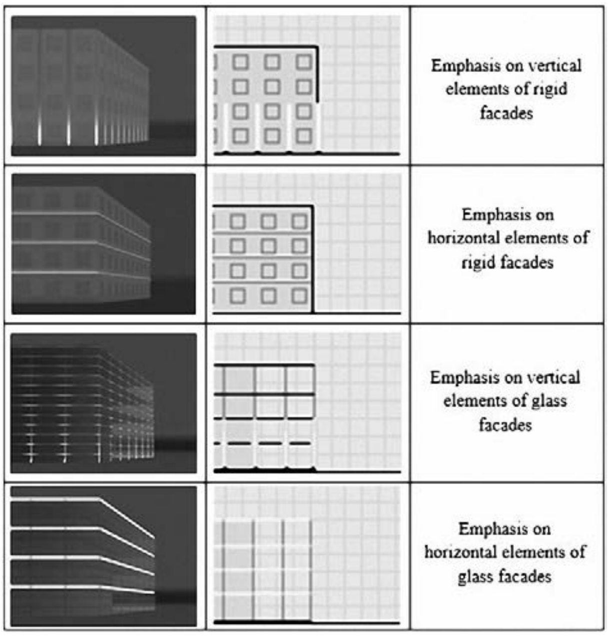

Fig. 2. Accent lighting with emphasis on vertical and horizontal elements of rigid facades and glass facades [21]

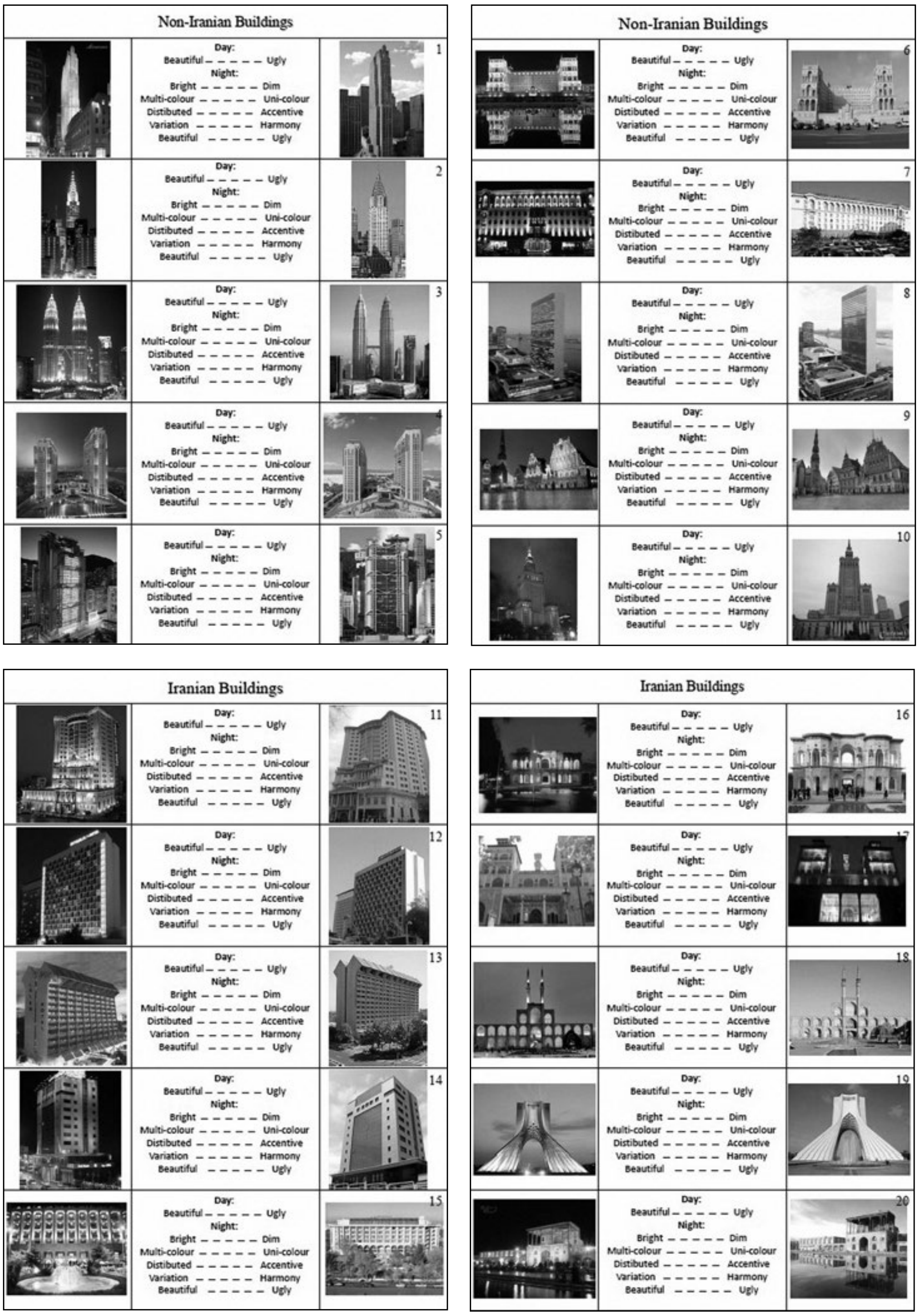

Fig. 3. The questionnaire

sible at night. Fig. 1 shows examples of uniform lighting of building facades.

Accent lighting emphasizes and highlights elements of a façade. These elements can be horizontal or vertical or specific elements of the architecture of the building such as its texture, material, structure, windows, or features such as a clock, sculpture, or ornament. To highlight an element, light is projected on that element from close up. This creates contrast between that element and the background (the rest of the façade). Another way of highlighting an element is to light the entire façade and highlight the borders of a specific element so that is stands out from the rest of the façade. Fig. **2** shows examples of accent lighting.

Attractiveness and visual variety are very important in nocturnal architecture and lighting of the considerable architectural buildings. Attractiveness and visual variety can be created by projecting colourful moving lights on the façade or by projecting patterns onto the façade. Colourful lighting, either in muted shades or primary colours, can make

Table 1. Buildings selected for study

Building ID	Building Name	Location
1	General Electric Building	US
2	Chrysler Building	US
3	Petronas Towers	Malaysia
4	Habtoor Grand Beach Resort	UAE
5	John Hancock Tower	US
6	Government House	Azerbaijan
7	Sheraton Sofia Hotel	Balkans
8	United Nations building	US
9	House of the Blackheads	Latvia
10	Palace of Culture and Science	Poland
11	Ghasre Talaee Hotel	Iran
12	Esteghlal Hotel	Iran
13	Laleh Hotel	Iran
14	Abresan Shopping Mall	Iran
15	Setareh Hotel	Iran
16	Shazdeh Garden monument	Iran
17	Shamsolemareh Palace	Iran
18	Mir Chakhmagh Square	Iran
19	Azadi monument	Iran
20	Ali Qapu monument	Iran

a façade more attractive. However, while the use of colourful lights (compared to white light) might increase attractiveness of a building, it may not necessarily increase the beauty of the façade [10].

3. RESEARCH METHODOLOGY

To study the effect of natural and artificial lighting on the perception of the beauty of buildings, a questionnaire was designed to perform field studies. The questionnaires offered photographs of the façades of 20 randomly selected buildings at night and in the day. This questionnaire was used to gather data from a statistical society of 50 individuals comprising three groups. The groups were 10 students of urban design, 15 students of architectural engineering, and 25 ordinary individuals with different levels of education. The individuals in the groups will likely have different criteria for their perceptions of beauty because of the differences in education and field of study. This provides confidence about the validity of the results.

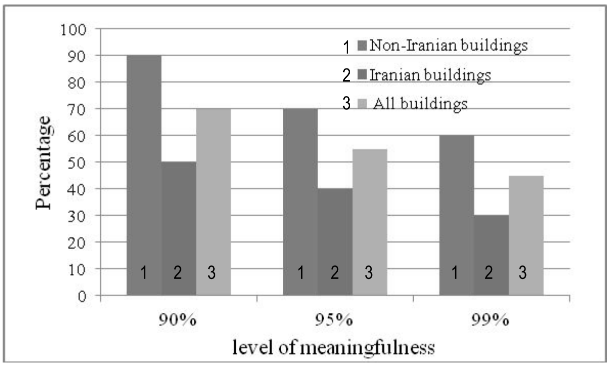

Fig. 4. Percentage of buildings exhibiting a valid hypothesis for similarity of beauty by day and night vs. level of meaningfulness

Participants were asked to rate the beauty of each building on a scale of 1 to 5 and to rate the effect of different lighting elements on the appearance of the building. SPSS software is used to analyze the collected qualitative data. We used semantic differentiation and bipolar adjectives to translate the qualitative data to quantitative values to evaluate the degree of influence of natural daylight and artificial exterior lighting on the perceived beauty of buildings and monuments.

3.1 Buildings selected for questionnaire

Twenty buildings were selected randomly as the objects of assessment in the questionnaire. These buildings are architectural monuments with different methods of lighting facade. Ten of these are in Iran and the rest are in other countries (Table 1).

These buildings are well-known due to architectural values or are monuments with different lighting designs. In addition to analyzing the effect of lighting on the beauty of the buildings at night, the effect of natural light was also examined. This allowed comparison of the effect of artificial lighting and natural daylight on the perception of beauty.

3.2. Design of questionnaire

The questionnaire featured photographs of buildings taken in daylight and at night. Participants were asked to rate the beauty of the each building under natural lighting and artificial lighting. The ratings were based on a five-level Likert scale (very low, low, average, high, and very high).

For nighttime artificial lighting, in addition to beauty, participants were asked to rate the elements of lighting design. These elements are the intensity, colours, prominence, and harmony of the lighting. All information was collected about the perceptions of beauty at night and in the daylight, as well as information about the effect of different elements of lighting design on the overall beauty of the building.

Fig. 3 shows the questionnaire used in the study.

4. ANALYSIS OF DATA AND STATISTICS

4.1. Validity of data

The validity of the questionnaire and the data gathered from participants was first determined using Cronbach's alpha. When Cronbach's alpha is greater than 0.7, it can be concluded that the questionnaire and data are valid. Otherwise, any conclusion drawn from the data will not be valid. The questionnaire examined six items for each building, making a total of 120 items (variables). SPSS was used to analyze the data. Cronbach's alpha was calculated to be 0.816, which indicates that the questionnaire and data collected was valid.

4.2. Beauty of façades by day and night

The Wilcoxon test was used to analyze the day and night beauty of buildings using the collected data. This is a statistical test suitable to study of the degree of correlation between variables. It can be used to determine the co-evolution factor of two variables. The absolute value of this coefficient specifies the extent to which variable are correlated and the sign denotes how the two variables are correlated. All test data should be of cardinal scale.

The validity of the hypothesis "the buildings are equally beautiful in daylight and at night" was first determined. The correctness of the hypothesis for each building was determined and the percentage of buildings for which it was valid was calculated.

The results of analysis are shown in Fig. 4 for different levels of meaningfulness. The level of meaningfulness specifies the confidence of the result. It was observed that at 99 %, more than half of the buildings were considered as beautiful at night as in the day. At 95 %, less than half of the buildings were perceived to have the same beauty. At 90 %, 30 % of buildings are considered of equal beauty. At all three levels, a small percentage of buildings have different levels of beauty during the day and night.

Fig. 5 shows the degree of similarity between perceptions of the beauty of each building in daylight and when illuminated at night. The average degree of similarity is provided for each group of buildings and for all buildings in Fig. 6. The results indicate that most participants felt that exterior lighting at night increased the beauty of most buildings over their appearance in daylight. This observation is also verified by Fig. 7, which shows the average points accrued for nighttime and daytime beauty of the individual buildings.

Fig. 8 indicates that artificial lighting at night made non-Iranian buildings appear more beautiful

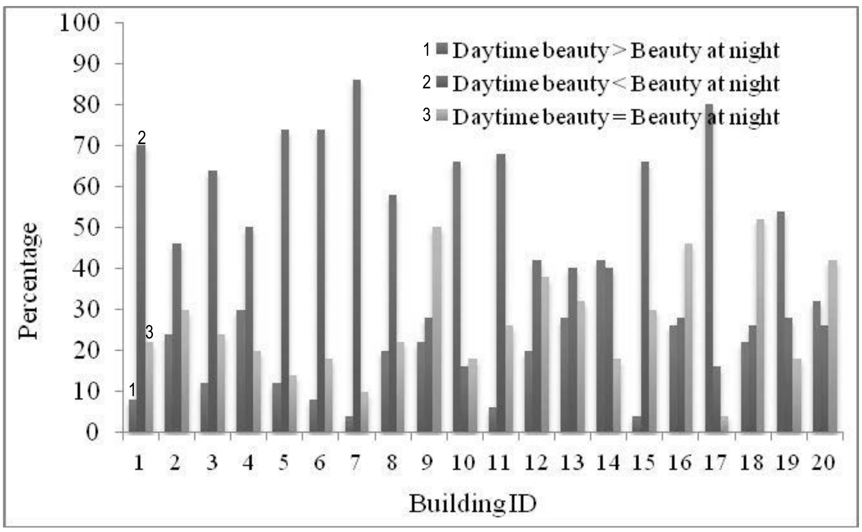

Fig. 5. Degree of similarity between perception of beauty of buildings in the daytime and at night

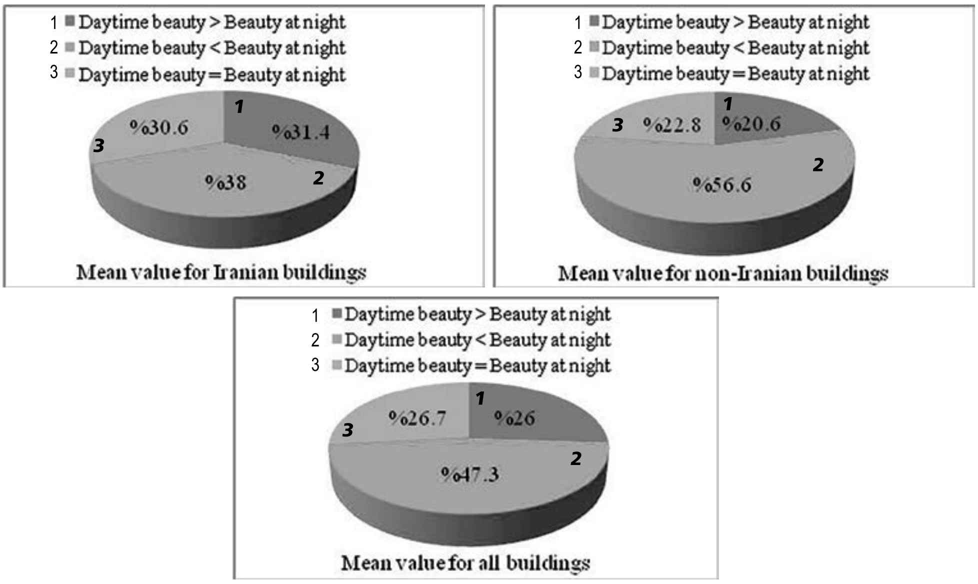

Fig. 6. Mean values for similarity of perceived beauty of buildings in the daytime and at night

than it did for Iranian buildings. Iranian buildings were perceived by the participants (which were all Iranian) to be more beautiful than non-Iranian buildings in natural daylight, but both groups were rated similarly for night lighting.

4.3. Effect of lighting elements on beauty of facades at night

At night, the beauty of a building is effecting by lighting elements. These elements are lighting intensity, colours used, accentuation, and the harmony of the lighting with the building. The results established a meaningful relation between the perception of beauty of buildings and each element; 90 % agreement was considered to denote a meaningful relationship.

The Spearman coefficient was used to determine the existence of such a relation for individual buildings. This coefficient shows the degree of correlation between two random variables. It takes a value between –1 and 1. When the Spearman coefficient for two variables equals 1, those two variables are directly related to each other. If one variable increases, the other will increase as well. When the coefficient takes a value of –1, it means that the two variables are inversely related; if one increases, the other will decrease. A value of zero means the two variables are not correlated.

Table 2 lists the results of this test and shows that the correlation between the elements of lighting and beauty of a façade at night varied from building to building. Because a meaningful correlation had been established using the Spearman coefficient,

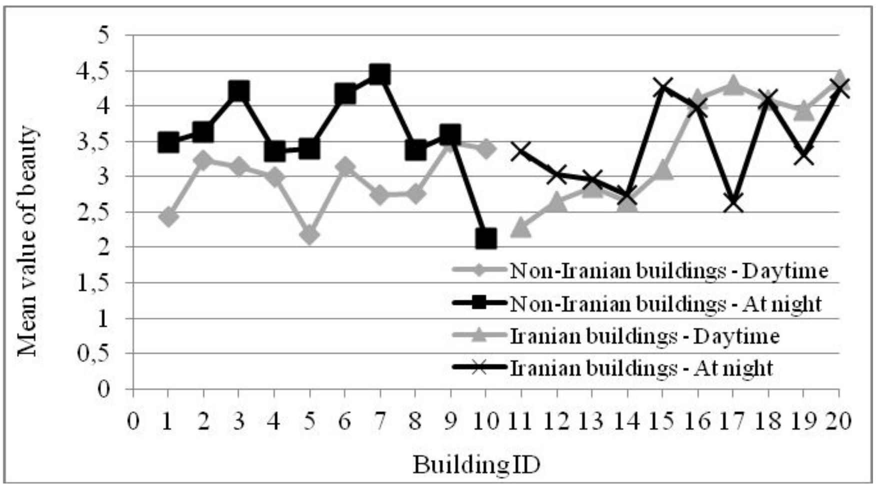

Fig. 7. Average points for perception of beauty of buildings in the daytime and at night

Table 2. Spearman's coefficients for elements of lighting and degree of perceived beauty of buildings; empty rows denote no meaningful relation for a level of meaningfulness of 90 %

Building ID	Lighting intensity	Colour diversity	Lighting uniformity	Lighting harmony
1	0.265	0.240		
2	0.241		–0.317	
3	0.283			
4				–0.262
5			–0.296	
6		–0.369		
7	0.453			
8				
9			0.241	
10	–0.315			
11			–0.364	
12				
13	0.455		–0.286	
14			–0.292	
15	0.440			
16		–0.269		–0.405
17		–0.303		–0.435
18		–0.584		–0.461
19				
20				
Average Spearman coefficient	0.260	–0.257	–0.219	–0.390

it could be concluded that the beauty of the façade was more closely correlated to the lighting method (uniform or accent lighting) than to lighting colour or harmony between the lighting and building. This was concluded because the correlation between the beauty of a façade and lighting method was observed for a majority of buildings.

The average correlation coefficient indicates that the perceived beauty of a façade had a direct relationship with lighting intensity. When the light intensity increased, the building was perceived as being more beautiful. The perceived beauty of a façade was found to be inversely proportional to lighting colour. If the single colour lighting was used, the

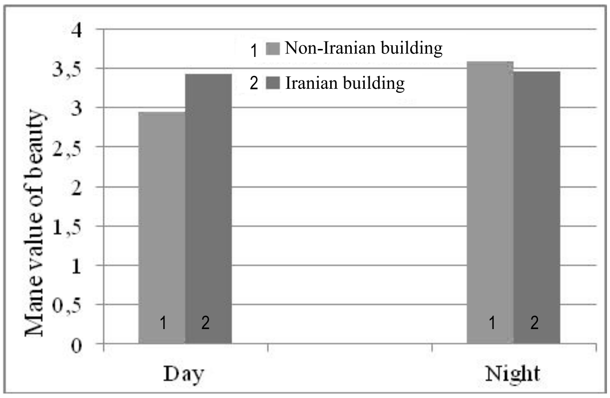

Fig. 8. Mean value for perceived beauty of Iranian and non-Iranian buildings in the daytime and at night

perceived beauty of the building increased compared to when multiple colours were used. In terms of lighting types, accent lighting increased the perception of beauty of the façade over the effect of uniform lighting. With respect to lighting condition, harmony between the lighting and the building also increased the perception of beauty of the façade at night over the lack of harmony.

5. CONCLUSION

The present study examined the effect of novel lighting techniques and its elements on perceptions about the beauty of facades of buildings at night. The elements studied were light intensity (low vs. high intensity), colour diversity (single vs. multiple colour), lighting type (accent vs. uniform), and lighting state (harmonized vs. diversified). The study was conducted using a questionnaire that was completed by 50 participants. The groups were 10 students of urban design, 15 students of architectural engineering, and 25 ordinary individuals with different levels of education. The questionnaire required the participants to rank the beauty of 20 buildings during the day (natural lighting) and at night (artificial lighting) along with the effect of each lighting element on the perceived beauty of the facades at night. The buildings selected were a group of Iranian and a group of non-Iranian buildings. The results were analyzed using SPSS to draw meaningful and scientific conclusions.

Analysis indicated that artificial lighting at night made a building appear more beautiful than it did in natural daylight. This was more recognizable in non-Iranian buildings than in Iranian buildings. Iranians buildings were perceived by the Iranian participants to be more beautiful than non-Iranian buildings in natural daylight, but both groups were rated similarly for night lighting. This study also suggests that as light intensity increased or when single-colour lights were used, buildings were perceived to be more beautiful at night. Accent lighting is where elements and levels of a façade are highlighted selectively rather than uniform lighting of the whole facade, and harmony between the lighting and building increased the perception of beauty of the facade at night as well. Lighting intensity and method (accent or uniform) had more influence on the perceived beauty of the façade than the other two elements.

The results of this research indicate the perceived beauty of buildings can be strongly effecting by proper lighting design. Although the design of façades and their appearance at daytime is important for the architect, the appearance of the façades at night is of high importance as well. This requires scientific and novel design of the exterior lighting of the buildings.

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PERFORMANCE ANALYSIS OF VARIOUS TYPES OF HIGH POWER LIGHT EMITTING DIODES

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ABSTRACT

Solid state, energy efficient light emitting diode (LED) technology is coming up to replace the conventional gas discharge, etc. light sources. Although declared life of LED is very high but in tropical countries their life time appears very short. This phenomenon is becoming the most drawbacks for usage of LED. To search out the reason for the failure lead to undertake thorough study on the performance of LED specifically on the various environmental conditions. Experimentation was carried out with various types of commercially available high power LED. Failure in tropical countries may be due to effect of temperature. Test results have been noted at various major parts of LEDs, e.g. die, and sink area. Detail analysis of test results at various parts of LEDs in different conditions tends to have some idea about the cause of failure of the LEDs in tropical countries with high ambient temperature and less scope of heat generation by the light source.

Keywords: chip on board (COB), heat sink, LED die, surface mounted devices (SMD), temperature

INTRODUCTION

Light emitting diode (LED) is a solid state lighting (SSL) device, which is mercury free, less hazardous, small wattage and provides high efficacy. LED can be used as any form of application from signage lighting to flood lighting. LED is a *p-n*-junction semiconductor device. When power is applied, the recombination occurs at *p-n*-junction and energy is released as photon in the form of light [1, 2]. In this recombination only some portion of electrical energy convert into light and the rest converts into the form of heat at the junction of the LED, which is determine the junction temperature [3]. The junction temperature of an LED is very important parameters because the light output, reliability and lifespan seriously depend on it. The electrical power is converted for the entire light source into the form of radiant and thermal energy [4, 5, 6]. For LEDs, a large portion of generated heat has to be dissipated by using conduction and convection process because this excessive heat may damage the LED devices. So, there must be needed an appropriate process to limit the temperature of the devices. Surface mounted devices (SMD) and COB type LEDs are required proper thermal management to minimize the generated heat from the devices to reduce the failures. The maximum junction temperature of the LED die or chip inside the package is based on the en-

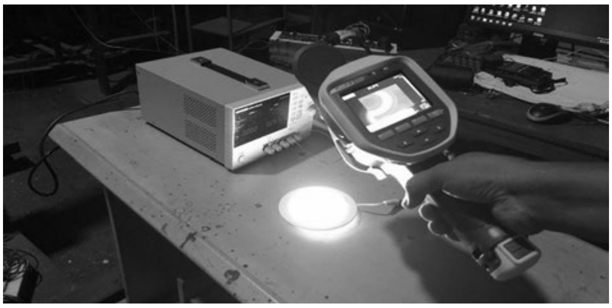

Fig. 1. Temperature measurement of the LED without driver by using Thermal Imager (Fluke Ti 400) methodology adopted

Table 1. Specification of LEDs

Sl. No.	Type of LED	Power rating, W	Dimensions* (mm)		LED mounting method	Material of heat sink	Electric Circuit of LED matrices
			DΦ	H			
1	SMD warm white LED	6	120	12	Recessed & Surface Mount	Aluminium alloy	Arrays are suitable arrange with series/parallel combination
2	SMD cool white LED	6	120	12	Recessed & Surface Mount	Aluminium alloy	Arrays are suitable arrange with series/parallel combination
3	COB warm white LED	5	88	40	Recessed ceiling down lighter	Aluminium alloy	Compact in-built chip
4	COB cool white LED	5	88	40	Recessed ceiling down lighter	Aluminium alloy	Compact in-built chip

*DΦ – Diameter, H- Height

durable thermal stress. But practically, it is impossible to maintain the proper rated value, which is provided the manufacturer due to this thermal imbalance in the LED devices.

TEST OBJECTS

The experiment has performed with four types of LED lamps of same make. Each and every LED are operated at 300 mA and they are listed in the Table 1.

EXPERIMENTAL SETUP

Experiments included two parts of a LED fixture, one is measurement of temperature near LED's chip and another is measurement the surface temperature of the LED heat sink. One Thermal Imager (Fluke make Model no: Ti 400) has been used to measure the temperature variations of a LED at different positions, Fig.1. Two COB type LEDs, where one is warm white type and other is cool white type, are affixed on the aluminium heat sink. The CCT of COB type warm and cool white LEDs are 3000K and 6500K respectively. Similarly, two SMD type LEDs where one is warm white type and another is cool white type and their CCT are 3000K and 6500 K respectively. The thermal measurement of LEDs are performed at ambient temperature T_a~ 28 °C. Duration of the thermal measurements is set to 60 minutes. LED was driven by the constant current LED driver with output current 300 mA.

The temperatures of the subject item have been taken at all die and sink areas of the subject LEDs as referred above. Initially temperature at ambient has been measured with Thermo couple type thermometer. The temperatures at die and sink areas of the subject LEDs have been measured through thermal imager (Fluke make, Model no. Ti400). First the temperatures are measured when each lamp connected with LED-driver circuit, at its rated condition. Temperatures are also taken from the lamps by connecting DC power supply without LED-driver circuit. Data has recorded at the initial condition when switch is turn ON and then at every five minutes interval up to one hour.

RESULTS AND DISCUSSIONS

The values of the test results are listed along with the characteristics curve obtained from the result. Few samples of IR images are also furnished here, where the LED is operated with driver. In Figs. 2 and 3**,** where the maximum temperature at sink area for COB type warm white LED at lamp start-up time is 99.1 °F or 37.27 °C and after 60 minutes of burning the lamp it is 127.1 °F or 52.8 °C respectively. Similarly for COB type cool white LED the maximum temperature at sink area is 98 °F or 36.6 °C when the lamp is just turn on, which is

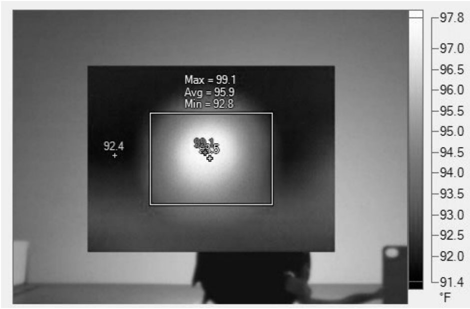

Fig. 2. Thermal image of COB type warm white LED at start-up time

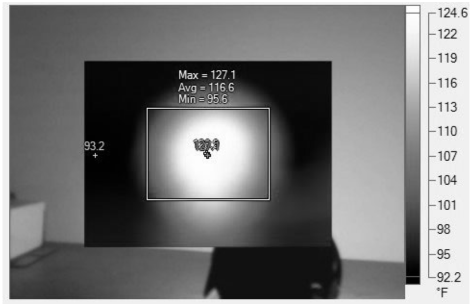

Fig. 3. Thermal image of COB type warm white LED after 60 min burning

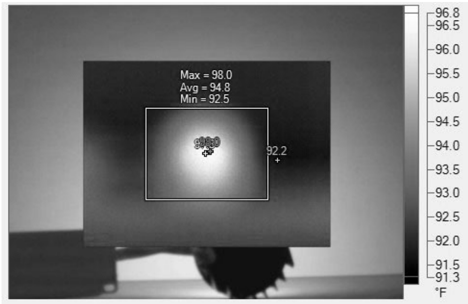

Fig. 4. Thermal image of COB type cool white LED at start-up time

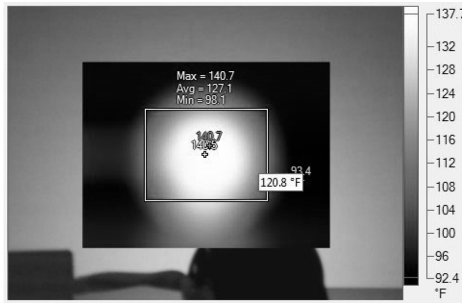

Fig. 5. Thermal image of COB type cool white LED after 60 min burning

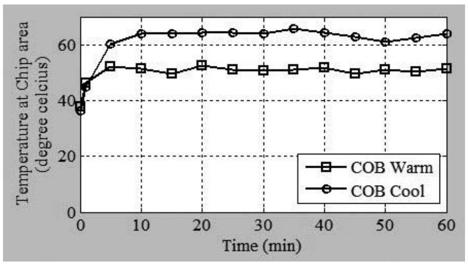

Fig. 6. Temperature at die area for COB type LED with time

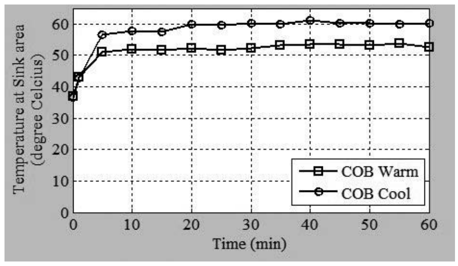

Fig. 7. Temperature at sink area for COB type LED with time

shown in Fig. 4. After 60 minutes of burning time, for same type of LED the temperature is 140.7°F or 60.3 °C which is shown in Fig. 5.

For COB warm white LED the temperature near chip area of the LED is not constant. The temperature increased to about 52 °C at five minutes burning time from its initial start up position. Then the temperature decrease slightly after five minutes to fifteen minutes of the LED's burning time. After that the temperature of the COB warm white LED is near about 50 °C. The temperature near the chip area for both of COB type warm and cool white LEDs are shown in Fig. 6. The temperature is raised up to 63.8 °C for first 10 minutes of its burning time for the COB type cool white LED. After 10 minutes for its burning time to one hour the average temperature of the LED is 64 °C. For both the LEDs the ambient temperature was 29 °C when the measurements have been taken.

The sink area temperature for both of COB warm and cool white LEDs are shown in Fig. 7. Similarly the temperatures at sink area are increased till five minutes of burning time for both the LEDs and after that the temperatures are nearly in constant manner. The temperature rise of COB type warm white LED is lower than COB type cool white LED.

The temperatures near the chip of SMD type warm and cool white LEDs are shown in Fig. 8. The temperatures of both type LEDs are increased for first fifteen minutes of their burning time. After that the temperature of the chip area observed as decrease for five minutes and then the temperature again increased. In this way, the temperatures are varied with respect to their burning time till steady state remains and equilibrium is reached through the

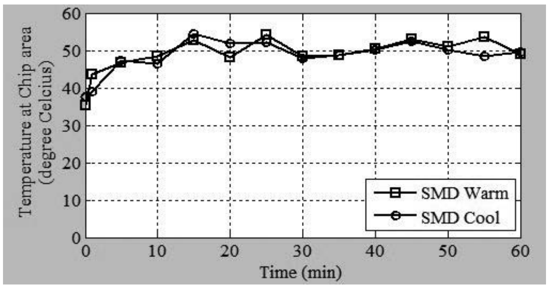

Fig. 8. Temperature at die area for SMD type LED with time

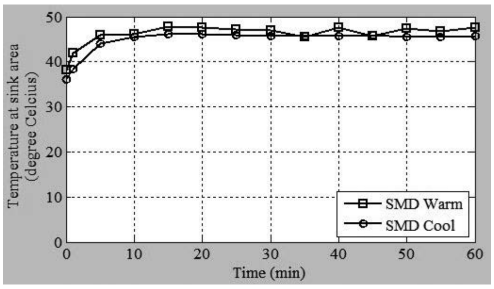

Fig. 9. Temperature at sink area for SMD type LED with time

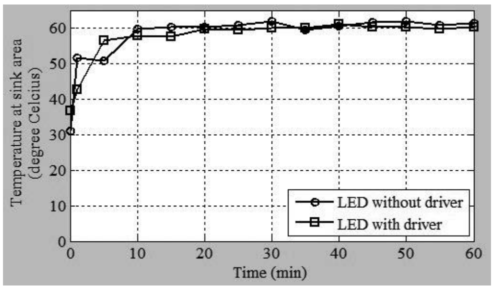

Fig. 10. Temperature at sink area for COB type Cool white LED without and with driver condition

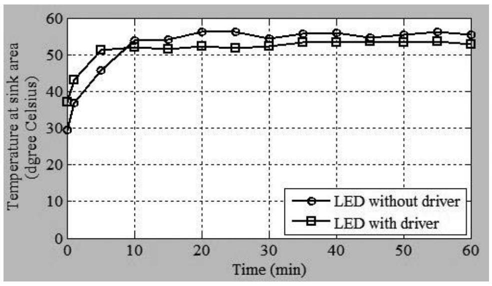

Fig. 11. Temperature at sink area for COB type warm white LED without and with driver condition

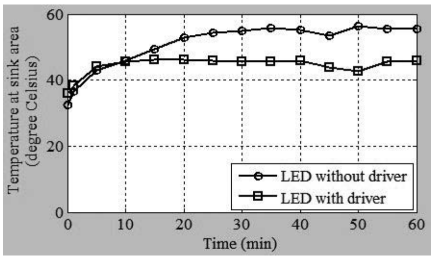

Fig. 12. Temperatures at sink area for SMD type cool white LED without and with driver condition

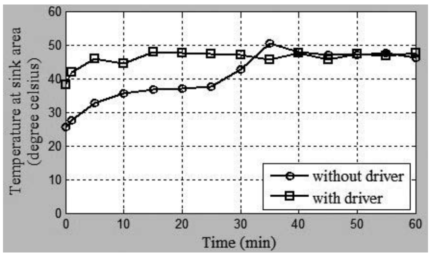

Fig. 13. Temperatures at sink area for SMD type warm white LED without and with driver condition

total generated heat distribution by conduction. For SMD type LEDs the temperature at the chip area of warm white LED is higher than cool white LED.

The temperature at sink area for SMD type warm and cool white LEDs are increased very rapidly within five minutes of their initial power on, which is shown in Fig. 9. After that the heat dissipation from chip area to sink area are occurred and the temperature at sink area of both type LEDs are decreased for few minutes. Because the generated heat from chip is dissipated to the sink area and then the heat at sink area is dissipated to the ambient. Again the temperature of the sink area is increased due to the heat generation of the chip area. The temperature rise at sink area for the SMD type cool white LED is lower than for the SMD type warm white LED.

To compare the temperature at sink area of the LEDs here the studies are occurred without driver. At start up time, the temperature at sink area of the COB type LEDs are less than the previous condition (with driver), which is shown in Table 2. But after ten minutes switch on the COB type Cool white LED for both the condition, the temperature is increased and higher than the LED luminaires with drivers, which is shown in Fig. 10. Similarly in Fig. 11 for COB type warm white LED, the temperature at initial time is lower when the LED devices without connection to driver but supply the DC rated voltage and after ten minute switch on the LED, the temperature is increased.

The sink area temperatures of SMD type warm and cool white LEDs for both conditions (without driver and with driver) are shown in Table 3. The temperature analysis of SMD type cool white LED is the next: the temperature is increased after ten minute of its switch on for when the lamp is without driver condition what is depicted in Fig. 12.

Table 2.Measured temperature distribution in sink area of COB type LED

Sink area temperature,°C				
	COB warm white LED		COB cool white LED	
Time (min)	Without driver	With driver	Without driver	With driver
Initial	29.6	37.0	31.1	36.6
1	36.9	43.0	51.7	42.7
5	45.6	51.2	50.7	56.6
10	53.8	52.0	59.8	57.9
15	54.1	51.6	60.3	57.6
20	56.1	52.2	60.2	59.8
25	56.2	51.7	60.9	59.5
30	54.4	52.2	62.0	60.1
35	55.7	53.3	59.4	59.9
40	55.9	53.4	60.4	61.2
45	54.7	53.5	61.5	60.3
50	55.5	53.2	61.9	60.2
55	56.1	53.7	60.8	59.8
60	55.5	52.7	61.3	60.3

But for a SMD type warm white LED the temperature at sink area is lower up to twenty five minute when LED is without driver condition and after that the temperature is approximately near the temperature when the LED connected with driver, Fig. 13.

The light output of both COB warm and cool white LEDs are decreased when the lamp is switch on and after 10–15 minutes, the light output of cool white LED is increased and near about 4300 lx, but for COB warm white LED the light output is approximately 3800 lx, Fig. 14. Similarly for SMD type LEDs, variation of light output with burning time is shown in Fig. 15. Where for SMD cool white LED the light output is averagely 1500 lx. But, light output characteristics are slightly different for SMD type warm white LED and the average illuminance value is equal to 1460 lx. The light output or illuminance was measured at 1 feet distance from the lamps.

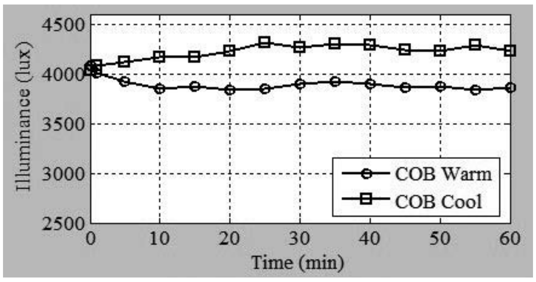

Fig. 14. Light output for different temperature at sink area when time in progress for COB type cool & warm white LEDs

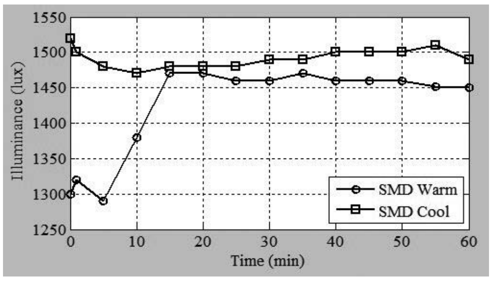

Fig. 15. Light output for different temperature at sink area when time in progress for SMD type cool & warm white LEDs

TEMPERATURE CALCULATION

Here only two types of COB LED module are used for the calculations of the temperature at sink area:

– Maximum case temperature of both the COB module is T_c = 85°;

– Ambient temperature of both COB module is T_a = 45 °C (as declared by manufacturer in their catalogue);

– Diode current, I_D =300mA and diode forward voltage V_f = 18 V dc;

Table 3. Measured temperature distribution in sink area of SMD type LED

Sink Area Temperature,°C				
	SMD warm white LED		**SMD cool white LED**	
Time (min)	**Without driver**	**With driver**	**Without driver**	**With driver**
Initial	25.5	38.2	32.5	36.1
1	27.6	41.9	36.6	38.4
5	32.8	45.9	43.0	44.1
10	35.5	46.1	45.9	45.6
15	36.7	47.8	49.4	46.1
20	37.0	47.5	52.8	46.1
25	37.5	47.2	54.4	45.9
30	42.8	47.0	54.8	45.7
35	50.4	45.6	55.9	45.7
40	48.0	47.5	55.1	45.8
45	47.0	45.7	53.4	43.9
50	47.0	47.3	56.3	42.6
55	47.7	46.8	55.4	45.6
60	46.2	47.6	55.4	45.8

Table 4. Temperature at heat sink area – calculated and measured values

Parameters	**Temperature at heat sink area,°C**	
	COB Cool type LED	**COB Warm type LED**
Calculated Value	63.096	58.096
Measured Value	60.772	55.272

Table 5. Statistical errors between calculated and measured data

Temperature at Heat sink Area	**RMSD,%**	**MBD,%**	**MPD,%**
COB Cool white LED	+ 0.048	+ 4.79	+ 3.824
COB Warm white LED	+0.071	+ 7.17	+6.67

– System power = 5.4 W.

a) For COB Cool white LED:

Maximum junction temperature T_j =105 °C;

Thermal resistance of the COB module $R_{j\text{-}c}$ is 3.6 °C/W, so, the maximum temperature added in the total design is $T_j - T_a$ = 60 °C. Here assume 80 % of total power to be dissipated (P_d) = 0.8 (80 %) × 5.4= 4.32 W;

Thermal resistance of the grease between COB module and heat sink is R_b =0.4 °C/W;

Now calculated case temperature $T'_c = T_j - (R_{j-c} \times P_d)$ = 105 °C – (3.6×4.32) = 89.448 °C; Then calculated $T_b = T'_c - (R_b \times P_d)$ = 89.448 °C – (0.4× 4.32) = 87.72 °C; Heat dissipated to the ambient (T'_a) is calculated and the value is $T'_a = T_b - (R_{th} \times 4.32)$ = 87.72 °C – (5.7×4.32) = 63.096 °C, where the thermal resistance of the heat sink R_{th} is 5.7 °C/W;

Now the measured average temperature at heat sink area is 60.772 °C.

b) For COB warm white LED:

Maximum Junction Temperature T_j =100 °C;

Thermal resistance of the COB module R_{j-c} is 3.6 °C/W;

So, the maximum temperature added in the total design is $T_j - T_a$ = 55 °C;

Here assume 80 % of total power to be dissipated P_d = 0.8, (80 %) × 5.4= 4.32 W;

Thermal resistance of the grease between COB module and heat sink is R_b =0.4 °C/W;

Now calculated case temperature $T'_c = T_j - (R_{j-c} \times P_d)$ = 100 °C – (3.6 × 4.32) = 84.448 °C;

Then calculated $T_b = T'_c - (R_b \times P_d)$ = 84.448 °C – (0.4 × 4.32) = 82.72 °C;

Heat dissipated to the ambient (T'$_a$) is calculated and the value is

$T'_a = T_b - (R_{th} \times 4.32)$ = 82.72 °C – (5.7 × 4.32) = 58.096 °C, where the thermal resistance of the heat sink R_{th} is 5.7 °C/W

Now the measured average temperature at heat sink area is 55.272 °C.

The final comparison between calculated and measured values can be seen in Table 4.

COMPARISON OF TEMPERATURE – CALCULATED AND MEASURED VALUES

The temperature measured on heat sink has been validated by calculated values obtained from simulation.

To assess the predictive accuracy of the theoretical simulation model, statistical indicators are used. The dimensionless statistical indicators, Mean Bias Deviation (MBD) and Root Mean Square Deviation (RMSD) are expressed as fractions of mean values during the respective time interval. The mathematical expressions for MBD and RMSD are given in equation (1) and (2) respectively as,

$$MBD = \left[\frac{\sum_{i=1}^{N} \left(T_{cal,i} - T_{meas,i} \right)}{N \times T_{mean}} \right] \times 100 \quad (1)$$

$$RMSD = \left(\frac{1}{T_{mean}} \right) \times \sqrt{\frac{\sum_{i=1}^{N} \left(T_{cal,i} - T_{meas,i} \right)^2}{N}} \quad (2)$$

The Mean Percentage Deviation (MPD) between calculated and measured temperature are given by the equations (3) as,

$$MPD = \frac{\sum_{i=1}^{N} \left[\frac{T_{cal,i} - T_{meas,i}}{T_{meas,i}} \right]}{N} \times 100 \quad (3)$$

The estimated errors between calculated and measured values of temperature at sink area are shown in Table 5.

CONCLUSION

Several experiments have performed for analyzing the nature of temperature distribution with same make of COB and SMD type LEDs, which have a number of applications in lighting field. So, it needs to be taken in consideration for observing the thermal behaviours for these types of LEDs in ambient conditions. The temperature generation at die as well as sink area of a warm white COB LED is lower than cool white COB LED. But for SMD warm white LED, the temperature of die and sink area is higher than the cool white SMD type LED. Another aim of this work is to find the temperature value when the LED lamps are drive with direct DC supply, i.e. directly without driver circuit; for this condition the temperature is almost higher than the LEDs, which are connected with driver circuit. From this temperature analysis designers can modify the construction of the LED for proper heat management.

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DAYLIGHTING PERFORMANCE OF MANUAL SOLAR SHADES

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ABSTRACT

The daylighting performance improvement of manual solar shades was compared with two conventional window scenarios. A developed stochastic model for manual solar shades was used for co-simulation by BCVTB. Results show that manual solar shades increase useful daylight illuminance by approximately 160 % compared to conventional windows with less significant daylight illuminance fluctuation. In addition, occupants operate solar shades effectively during the late spring and early summer and the manual control during other periods can be further improved to enhance daylighting performance.

Keywords: manual solar shades, daylighting performance, useful daylight illuminance

1 INTRODUCTION

Daylighting is the controlled admission of natural light into a building in order to reduce artificial lighting energy consumption. By providing a direct link to the dynamic and perpetually evolving patterns of outdoor illumination, daylighting helps create a visually stimulating and productive environment for building occupants. Daylight is considered to be an important factor for workers' satisfaction in an office space, since it provides office workers with psychological benefits in the space where artificial lighting systems create uniform and monotonous visual environment. To maximize daylight utilization, buildings are now designed with large windows or glazing curtain walls, which, in turn, could also increase the cooling load in summer or accelerate heat loss in winter. For example, intense daylight leads to glare problems at the perimeter zone and daylight with excessive solar gains leads to the increase of cooling energy consumption. In addition, direct sun in the eye of a building occupant can cause disability glare, which interferes with the occupant's ability to see and perform work and should be avoided. To have a controlled daylighting performance, solar shading devices are usually used, which can be designed to prevent overheating, to reduce heating losses and cooling loads, and to control the visual environment.

The adoption of movable solar shading devices to reduce the energy consumption and control daylighting performance was reported by researchers. For example, Staziet et al.[1] compared different fixed shading devices in terms of daylighting factors in a Mediterranean climate. Esquivias et al. [2] studied the daylight performance of overhangs and side fins in an open-plan office. These kinds of shading devices are fixed on buildings and thus need to be long enough to block excessive daylight due to the relatively low solar altitude angle in east and west directions. On the other hand, movable shading devices can be adjusted according to changing outdoor conditions in order to achieve minimal lighting energy consumption while at the same time offering a comfortable daylighting environment. Nielsen et al. [3] analyzed the daylighting performance of movable solar shading devices in office buildings. They found that the use of dynamic solar shading dramatically improved the amount of daylight available if compare to fixed solar shading.

However, this research was based on automated shading devices which mean that a complex con-

Table 1. Characteristics of the office room

Parameter	Value
Location	Ningbo city in China, latitude: 30º, longitude: 120º
Room orientation	South
Dimension	Room: 4×4×3m, Window: 3.8×2.8m
Window and shading device	Three window settings for comparison: 1) Clear double-pane window (CL), visual transmittance: 0.89; 2) Low-E double-pane window (LOW-E), visual transmittance: 0.69; 3) Clear double-pane window +manually controlled external shading (Shade), shade material visual transmittance is 0.2.
Daylight illuminance calculation point	Occupant position in Fig.1, 0.75m above the floor

trol system will be required to maintain the frequent change of shade positions or angles and they are more expensive than manually controlled shades. In China, most office buildings only use manually controlled roller shades [4]. Moreover, occupants' shade control is not as efficient as motorized systems since occupants' behavior is stochastic [5–7]. Therefore, the daylighting performance of manual solar shades should account for the stochastic characteristic of occupants' behavior.

2 METHODOLOGY

2.1. Building model

A typical office room model was used in this paper. Its dimensions are 4×4×3m with a 3.8×2.8m window on the south facade as shown in Fig.1. To compare the performance of manual solar shades with bare windows in terms of daylighting, three window settings were considered. The first two scenarios (clear double-pane windows and low-e double-pane windows) are the most popular design measures in this region. The last scenario represents exterior manual solar shading devices. The characteristics of the office room and the three scenarios are shown in Table 1.

2.2. Stochastic model of manual solar shades

To investigate the impact of manual solar shades on daylighting performance, the stochastic model developed in a previous study by the author [4] was used in this paper. The model was constructed based on field measurements on a typical high-rise glazing building in hot summer and cold winter zone of China. The measurement used a TB-2 pyranometer and PC-2 data recorder installed on the building roof to measure the total solar radiation on south facade and the shading adjustment of south facade of a glazing building located in Ningbo (about latitude 30 degrees North) was recorded by photographing the shades manually per hour. According to the previous research [4], considering five shade states is adequate for building simulation. Therefore, occupants' shade control was divided into 5 solar shading states (shade window area of 0 %, 25 %, 50 %, 75 % and 100 %, respectively). The measurement was carried out during the year in 2011. Though many environmental factors (such as daylight illuminance, glare) influence shade control, these factors can be direct-

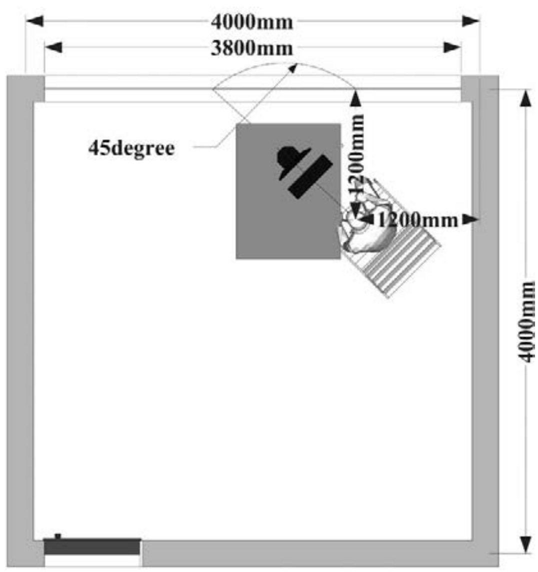

Fig.1. Room model showing the workplace position (upward direction represents South)

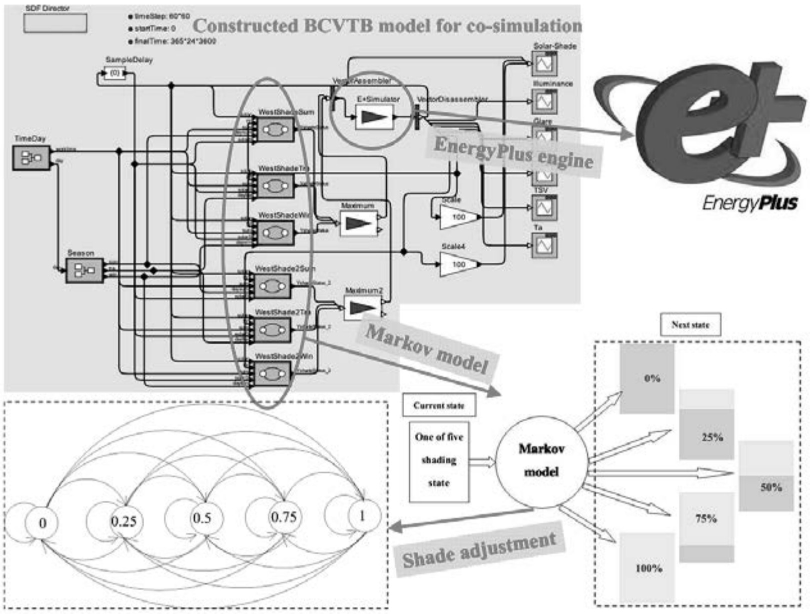

Fig.2. A graphic illustration of the developed method for co-simulation of the daylighting performance of manual solar shades

ly or indirectly linked to solar radiation, and thus daylighting index was not measured. After field measurement, further logistic regression analysis showed that solar radiation is the driving factor (compared to other thermal factors such as outdoor air temperature) of shade adjustment behaviour. Therefore, a first order and time-constant Markov chain method was used to construct the stochastic model of solar shade control based on solar radiation, and the Markov chain transition matrix (the probability of solar shade changes from the current state to the next position) for different sky conditions were calculated and classified. In order to better reflect the occupant behaviour of controlling shades under different sky conditions, the threshold of receiving direct solar radiation (here it is about 300 W/m^2 according to field measurements) was considered as the dividing line to construct transition matrix. After that, the Markov model for solar shades was modelled in BCVTB for co-simulation with EnergyPlus. At each time step, BCVTB will check the solar radiation intensity on external windows from EnergyPlus and then randomly generate a shade position according to the probability distribution and this shade position will then be applied in EnergyPlus simulation. A brief description of how this stochastic model is constructed and the co-simulation is conducted can be seen in Fig.2. More detailed information of this stochastic model and the co-simulation can be found in the previous paper [4].

2.3. Performance index

To have a comprehensive evaluation of daylighting performance, three indices have been adopted to assess the daylighting and glare protection performance. These indices include useful daylight illuminance (UDI), daylight illuminance fluctuation, daylight illuminance distribution. UDI determines when illuminance levels are useful for the occupant, that is, more than 300 lx [8] (not too dark) and less than 2000 lx (not too bright), [9]. Additional electrical lighting may be needed when the daylight illuminance is less than 300 lx, while glare may occur when daylight illuminance is over 2000 lx.

Fluctuation of daylight illuminance is also an important factor in influencing daylighting performance. At present, there is no equation or index for calculating daylight illuminance fluctuation (DIF) and thus the authors have introduced the standard deviation as the evaluation index. This can be expressed as follows:

$$E_\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(E_i - E_{ave})^2}, \qquad (1)$$

where E_σ is the standard deviation of daylight illuminance, N is the number of calculation points for daytime working hours (from 8:00 to 17:00, 10 points: 8:00, 9:00, …, 17:00), E_i is the daylight illuminance for i^{th} calculation point, and E_{ave} is the ave-

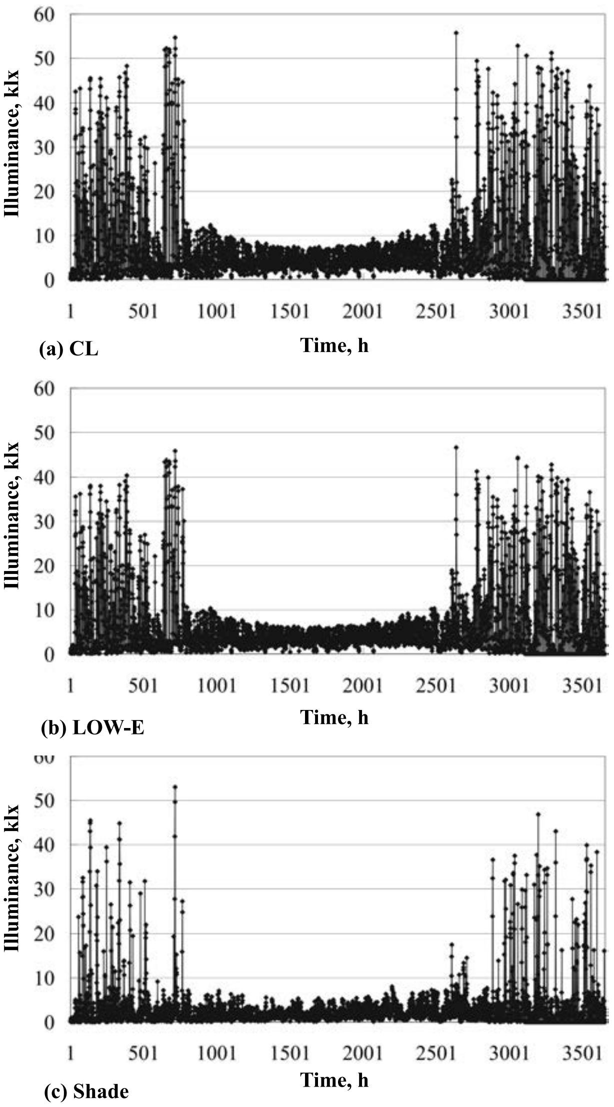

Fig.3 Daylight illuminance for the three measures during annual working hours (calculation point number is (D-1) x 10 + m, where D is the day of the year number and m = 1 for 8:00, 2 for 9:00, …, 9 for 16:00, 10 for 17:00

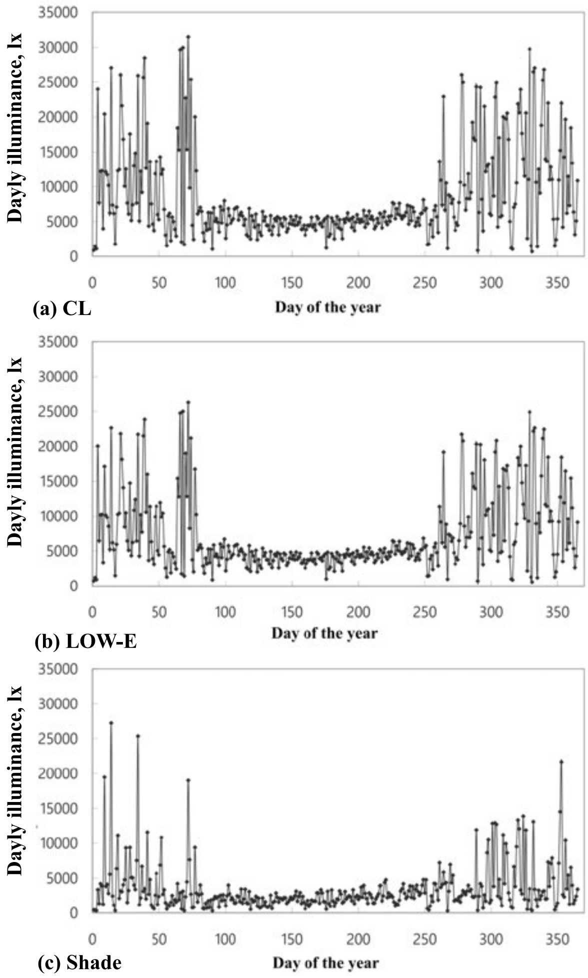

Fig.4 Daily average daylight illuminance for the three measures

rage daylight illuminance of the working hours for a day as shown below:

$$E_{ave} = \frac{1}{N}\sum_{i=1}^{N} E_i. \qquad (2)$$

3. RESULTS AND DISCUSSION

3.1. UDI

Daylight illuminance for the three measures during annual working hours is shown in Fig.3. Bare window scenarios (CL and LOW-E) have more hours with high daylight illumimance values compared with Shade. The daylight illuminance was further categorized into three groups, Table 2, according to UDI index. Shade has a total UDI of 1553 h (corresponding to a 42.55 % of working hours), followed by LOW-E (597 h, 16.36 %), and the poorest measure is CL (470 h, 12.88 %). That means manual solar shades perform better than the other two measures by approximately 160 %. Although manual solar shades have a little negative impact with more hours of daylight illuminance less than 300 lx, their positive impact of reducing potential glare risk is more significant with a reduction of daylight illuminance over 2000 lx by more than 1000 h compared to LOW-E and CL.

3.2. DIF

The daily average daylight illuminance for the three measures is illustrated in Fig.4. For this index,

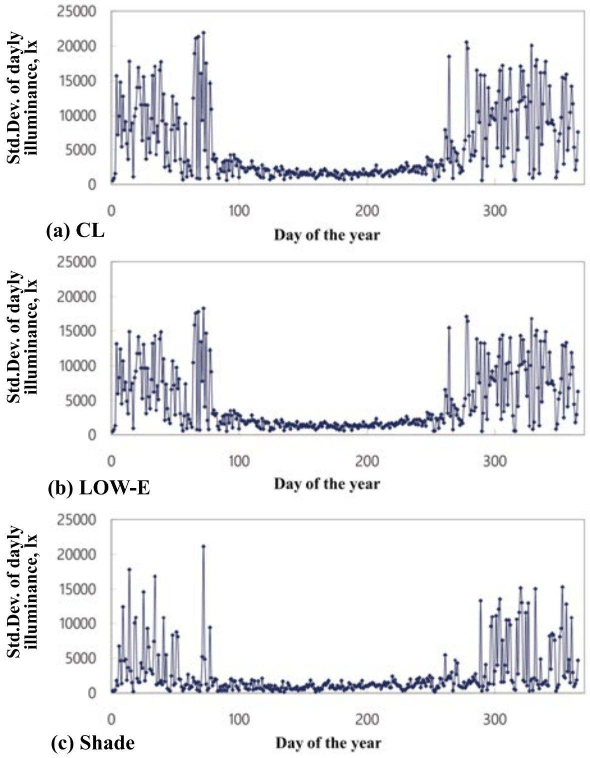

Fig.5 Daily standard deviations of daylight illuminance for the three measures

CL and LOW-E are both higher than 5000 lx, while shade is only about 2500 lx. This means that manual solar shades are more beneficial compared with bare windows (CL and LOW-E) according to the UDI range. On the other hand, the daily standard deviations of daylight illuminance are shown in Fig.5. It can be seen that manual solar shades also perform better with an improvement of about (44–53)%, Table 3, when compared to LOW-E and CL, respectively. This is because solar shades can be manually controlled by occupants in response to changing sky conditions and, thus, daylight illuminance on the working zone will be maintained at a relatively comfortable level.

3.3. Daylight illuminance distribution

Due to the stochastic characteristic of manual solar adjustment by occupants, it is important to understand when shades are adjusted and maintained at a suitable position that daylight illuminance is kept at UDI range (300–2000) lx. Fig.6 presents daylight illuminance distribution during the working hour of the whole year for the three measures. It can be seen that CL and LOW-E have very similar performance with almost the same UDI distribution. This is because they are all transparent windows

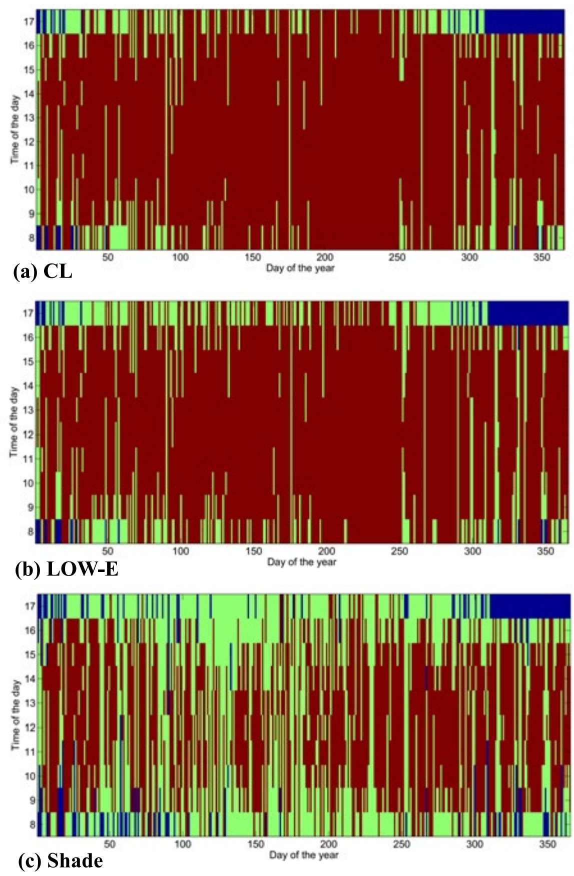

Fig.6. Daylight illuminance distribution during the working hour of the whole year for the three measures (blue:<300 lx, green: (300–2000) lx (UDI), red:>2000 lx)

with only little difference in visual transmittance. And UDI occurs only during early morning and late afternoon when sun light is not very bright. However, shade has more green area during the whole day, especially in late spring and early summer period. This is due to the more frequent use of solar shade compared to other periods. From this figure, it can be concluded that occupants operate solar shades effectively during the late spring and early summer and the manual control during other periods can be further improved to enhance daylighting performance.

4. CONCLUSION

This paper simulates the daylighting performance of manual solar shades and compares its performance improvement with two conventional window scenarios. Results show that manual solar shades increase UDI by approximately 160 % compared to conventional windows with less significant daylight illuminance fluctuation. In addition, occu-

Table 2. Daylight illuminance distribution

	Daylight illuminance, lx	CL	LOW-E	Shade
Hours	<300	89	95	229
	300–2000	470	597	1553
	>2000	3091	2958	1868
Percentage,%	<300	2.44	2.60	6.27
	300–2000	12.88	16.36	42.55
	>2000	84.68	81.04	51.18

Table 3 Annual average of E_{ave} and E_σ for the three measures

Illuminance, lx	Cl	LOW-E	Shade
E_{ave}	8461.48	7081.41	3358.12
E_σ	5341.93	4471.99	2524.83

pants operate solar shades effectively during the late spring and early summer and the manual control during other periods can be further improved to enhance daylighting performance.

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PHOSPHORS AND FLUORESCENT CONVERTERS IN LIGHT SOURCES WITH BLUE LED CRYSTALS

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ABSTRACT

The article presents a review of fluorescent material use: inorganic phosphors, organic polymeric and molecular phosphors, complex (coordination) compounds, quantum dots and frame metal-organic compounds as component materials of fluorescent converters to transform radiation of blue and ultra-violet diode crystals to white light.

Keywords: organic and inorganic fluorescent materials, white light emitting diodes (WLED), low pressure (LP)

1. INTRODUCTION

The use of phosphors in light sources began from fluorescent lamps (FL), in which UV radiation from LP mercury discharge is transformed to visible light by phosphor deposits on the walls of the discharge tube [1]. Twenty years ago, the concept of fluorescent transformation was also used to obtain white light from blue crystals (BC) LEDs [2]. It is clear that FL and LED lamps are closely related in terms of fluorescence.

This review is dedicated to the twenty-year long history of approaches and attempts to getting white light using energy efficient BCs and to a lesser extent, diode UV crystals (UVC) as primary radiation sources (RS).

FLs transform the consumed electric energy to UV radiation effectively, with energy efficiency greater than 64 % [3], whereas BCs are only about 50 % efficient [4]. However, transformation of LP mercury discharge UV radiation to visible radiation associated with significant energy losses. The main reason for this is Stokes shift. If exciting radiation frequency is ν_{ex}, and emitted frequency is ν_{em}, then the difference $h(\nu_{ex} - \nu_{em})$ expresses thermal losses, because $\nu_{em} < \nu_{ex}$. In FLs, frequencies of exciting mercury lines 254 and 185 nm differ from frequencies of visible radiation by several orders of magnitude, whereas, when fluorescent transforming of BC blue radiation, frequencies of exciting and emitted radiation belong to the visible spectrum and on average differ by less than 1.5 times. In the case of co-operative fluorescence (a type of anti-Stokes fluorescence), Stokes losses are absent, and energy efficiency of a near infrared laser as a primary RS is 50 %.

An optical device placed in the way of the luminous flux from the primary source of electromagnetic radiation, absorbing this radiation and emitting light by means of fluorescence, is a fluorescent converter (FC). There are two types of fluorescent crystals: fluorescent screens (FS) and fluorescent filters (FF), which differ in that FSs do not pass, and FFs pass primary RS radiation. The operational efficiency of an FC as an energy converter is determined by phosphor quantum efficiency (PQE). For FCs as optical devices, methods of exciting radiation input into the FC and of emitted radiation output are very important, but beyond the scope of this review. Methods of FC location relative to the localized primary RS, which is BC, can be divided into two types: the FC is next to the BC (version 1), or the FC is located at a distance away from the BC (version 2).

The first attempts to create white LEDs with FCs were announced in 1997. P. Shlotter, R. Schmidt and J. Schneider introduced fluorescent green, yellow and red perylene dyes or yellow inorganic phosphorus $Y_3Al_5O_{12}$: Ce^{3+} into epoxy resin (ER) adjoining the BC [5]. As a result, white LEDs based on BCs were developed in both cases. A similar result was obtained by A. Heeger and co-workers also in 1997. They used FCs (FFs) based on a fluorescence polymer, which emitted yellow fluorescence when exciting BCs in the FC distant location version [6]. Finally, a book [7] was issued, which described the creation of BCs and subsequent work carried out by S. Nakamura et al. for many years with Nichia, including the development of white LEDs. These developments used $(Y_{l-a}Gd_a)_3(Al_{1-b}Ga_b)_5O_{12}$: *Ce* composition phosphorus as the phosphor (a, b = 0–0.5), and demonstrated how white light of different chromaticity could be obtained by changing the composition of the phosphorus. The colour coordinates (CC) of the white light obtained in [5] are unknown; and for the specimens developed in [6], they were (x and y) 0.34 and 0.29, 0.41 and 0.32, and 0.55 and 0.38 respectively. S. Nakamura's White LEDs had CCs of 0.29 and 0.30 and a luminous efficacy (LE) of 5 lm/W [7]. All of the publications mentioned above correctly predicted that LEDs with FCs would find application as light sources for illumination.

After 1997 the number of studies which sought to obtain white light suitable for illumination based on BCs, UFCs and FCs increased drastically.

2. INORGANIC PHOSPHORUS

One successful discovery by the authors of [5, 7, 8] was the use of yttrium – aluminium garnet alloyed with cerium (*YAG: Ce*), which became a basic FC material for BCs. It absorbs in the blue spectrum interval and it is steady when exposed to increased temperatures and irradiance [2, 9]. In the best specimens, it had a fluorescence quantum efficiency of more than 0.81 [10], and in commercial specimens (in 2006) the quantum efficiency was between 0.61 to 0.70 [11]. A review of literature concerning phosphorus application up to 2014 can be found in [12].

The subject of many studies is the technology of growing the phosphorus crystal and of its variants within white LEDs (casting material, powder or nanocomposite) [13–20].

In many studies, compositions were tested wherein yttrium and cerium ions were replaced with ions of other rare-earth elements [21–26]. From the *YAG: Ce* phosphorus group, especially interesting is the *Gd-YAG: Ce* composition, in which yttrium ions were partly replaced with gadolinium ions [27–29]. *Gd-YAG: Ce* has an increased thermal stability. Whilst the luminance of *YAG: Ce* fluorescence decreases by more than 60 % with increasing temperature from 25 to 205 °C, then luminance of *Gd-YAG: Ce* decreases by only 20 %. *Gd-YAG: Ce* provides a high luminous efficacy: 144 lm/W with a correlated colour temperature T_{cc} = 5639 K and 127 lm/W with T_{cc} = 4490 K.

Thermo stable phosphorus K_2TiF_6: Mn^{4+} without rare-earth elements was obtained with a red glow and quantum efficiency of 0.98 when exciting by blue radiation [30]. FC specimens based on yellow phosphorus *YAG: Ce* and on red phosphorus K_2TiF_6: Mn^{4+} operating with BC (455 nm) allowed obtaining light with a T_{cc} of 2700–2800 K, R_a of 83–85 and LE of 99–124 lm/W.

With a view to simplify the production technology of lighting devices based on blue crystals, the idea placing the FC at a distance is popular. Study [18] presents an FC production method with a glass ceramic disc filled with fluorescent ultra disperse powder *YAG: Ce*.

The practical outcomes of the result of all this research into FCs based on inorganic phosphorus is broad range of white LED lamps available today.

3. ORGANIC FLUORESCENT CONVERTERS

3.1. Polymeric phosphors

Materials composing a polymeric FC [6, 31] are adjoined (conjugated) polymers like polyphenylene vinylene: poly(2-methoxy-5-(2′-ethylhexyloxy)-1.4-phenylene vinylene) ***1,*** Fig.1, poly(2- methoxy-5-(2′-ethyl- hexyloxy)-1.4-phenylene vinylene)-co-(2-butyl-5-(2′-ethyl-hexyl)-1.4-phenylene vinylene) ***2***, etc. These polymers are phosphorescent in the visible spectrum and strongly absorb light in the blue interval, where absorption factors are about 10^5 cm^{-1}. Specimens of the polymeric FCs were produced from submicronic layers of conjugated polymers, which were protect-

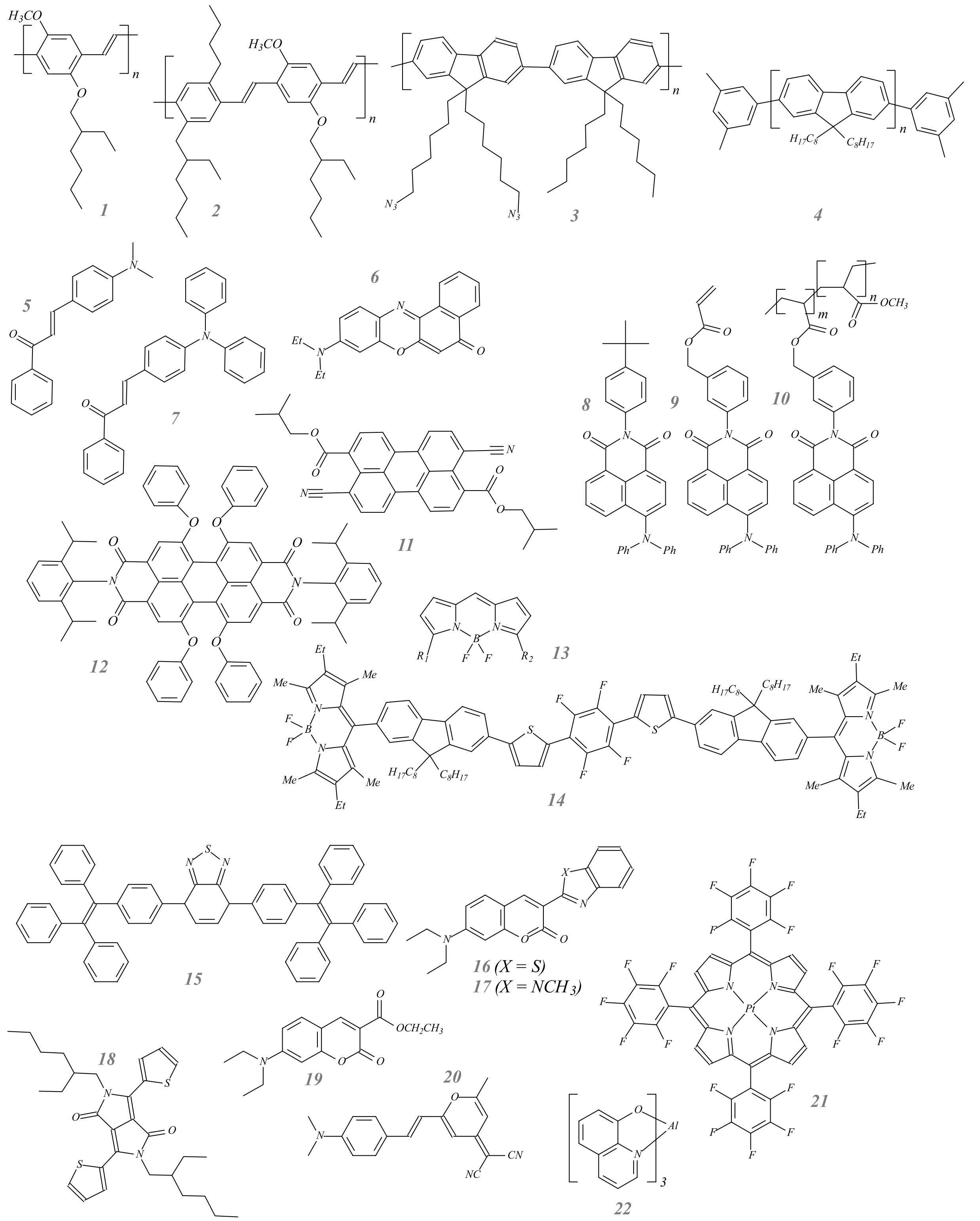

Fig. 1. Structural formulas of some phosphors

ed from the external environment by layers of glass or by encapsulation. Polymeric FCs were located at a distance from the primary RS from the outset. The best specimens had fluorescence quantum efficiency at a level of 0.6 [31, 32]. Using polymeric FCs with different BCs allowed obtaining light with colour coordinates very close to those typical for white colour. During tests lasting for more than 4000 hours, specimens of polymeric FCs showed stability no less than BCs.

Articles [33–35] are dedicated to the application of polyfluorene in white light sources. The studies [33, 34] report obtaining polyfluorene ***3*** with a molecular weight of about 20000 (n ≈ 40) and with azyid lateral groups. These groups provide interlinking of the polymeric chains. The polymer had fluorescence of white colour with a quantum efficiency of 0.86 at UV excitation. FSs of this polymer in operation had CC = 0.2554 and 0.2426, T_{cc} = 32400 K and *Ra* = 91. In [35], the FC material was a polymeric composite material: polyfluorene ***4*** with blue fluorescence and quantum points (QP) based on *CdSe/ZnS* with blue and yellow fluorescence were added to a polymethyl methacrylate (PMMA) matrix. This material was deposited directly on an UFC in specific proportions. FC specimens based on polyfluorene ***4*** and QPs with yellow fluorescence, emitted white light with T_{cc} from 3000 to 9000 *K* and with *Ra* = 85–90. In spite of the fact that quantum efficiency of polyfluorene ***4*** and of the obtained QP fluorescence was high (0.9 and 0.52 respectively), qthe uantum efficiency of the FC itself was 0.17, and LE was of about 13 lm/W. No results on FC stability were reported by [33–35].

3.2. Molecular phosphors

Several studies over the last 20 years explored the possibility of using molecular phosphors in FCs. FCs based on 4-dimethylaminochalcone ***5*** and on Nile red (7-diethylamino-3.4- benzophenoxazone ***6***) in an ER matrix were tested [36]; 4-dimethylaminochalcone ***7*** in polyethyleneglycol (PEG-6000)[37]; 4-N, N-diphenyl-9-(4-tret-butylphenyl)-1.8-naphthalimide ***8*** and fluorescein (as uranine) in ER and PMMA were tested [38]. FCs based on a copolymer of naphthalimide derivative **9** with PMMA ***10*** of the distant location type had stable characteristics within 12 days of uninterrupted operation [39]. However, the quantum efficiency of fluorescence compounds ***9*** and ***10*** were significantly lower than that of ***8*** with PMMA (0.65; 0.36 and 0.96 respectively). Studies [40–43] were dedicated to the application of yellow fluorescent *Lumogen F 083 11* dye and of red *Lumogen F 305 12* in FCs. Bor-difluoro derivative of dipyrrolmethane ***13***, namely compound ***14,*** was used in FCs for BCs in [44]. Aggregation phosphor 4.7-bis [4-(1,2,2- triphenylvinyl) phenyl] benzo-2,1,3- thiadiazole ***15*** was used in study [45].

Coumarine – 6 ***16***, coumarine 30 ***17*** and N-alkylated dipyrrolopyrrol with thiophen substitutes ***18***, as well as 7 (diethylamine) – coumarine-3-carbonic acid ***19*** and 4-(dicyanomethylene)- 2-methyl-6-(4-dimethylaminosteral) – 4H-pyran 20 were the basis of the FC in [46–48].

A noticeable degradation of phosphors in the listed publications was observed during operation from 10 min [45] up to 10 days [48].

3.3. Coordination compounds

Metal-porphyrines and coordinated compounds of metals are prospective materials for optoelectronics. In [49], their possible application in FCs is illustrated by using platinum (II) *meso*-tetrakis (pentafluorophenyl) porphyrine ***21*** and tris (8–8-oxyquinolinate) of aluminium (III) ***22***. The fluorescence of compound ***21*** in a PC matrix did not change at 120 °C during 1000 hours of operation. The intensity of fluorescence ***21*** decreased by one third after UV radiation with irradiance of 10 W/m^2 during 100 hours. UFC radiation with a certain concentration of compounds ***21*** and ***22*** transforms into white with a CC of 0.32 and 0.31, FI = 90.6, T_{cc} = 6800 K at LE =10 lm/W.

3.4. Quantum points

The first explorations of the possibility of using quantum points (QP) in FCs for LEDs are presented in [50, 51]. In [50], white light was obtained by a combination of blue fluorescence of an organic polymer with green and red fluorescence of *CdSe* of two types (3 and 7 nm in size), and in [51] *CdSe* QPs of a single type (1.5 nm in size) was used. The QPs synthesised in [51] had a wide radiation spectrum, an expressed edge in the long-wave absorption band and a relatively large Stokes shift. The authors reported on 10 days of operation stability but the material fluorescence quantum efficiency was very low, about 0.02. In nanotechnology literature properties of QP fluorescence describe quite opposite parameters: a narrowness of the radiation spectrum, a wide absorption band and a high quantum efficiency. The "narrow-band" QPs are soon likely to become the fluorescent material replacing technologies based on organic LEDs in colour displays (*Colour IQ* system by *QD Vision*). Meanwhile "broadband" QPs have not successfully increased their quantum efficiency to an acceptable level.

An example of successful use of the "narrow-band" QPs with yellow fluorescence in FCs for BCs can be found in study [52]. It was achieved using colloidal QPs with a core of *Cu-In-S* material of

Cu/In = ¼ relation, with two *ZnS* protective shells. The QP core size is 2.72 nm. These QPs had a high fluorescence quantum efficiency of 0.92–0.97. An SiO_x polymer was used to protect the QP layer from O_2 penetration and from its destuctive effect.

3.5. Frame metal-organic compounds

Frame metal-organic compounds (FMC) are a new class of crystal materials, which consist of transitional metal and of polydentate organic ligand cations.

A specific feature of the frame metal-organics crystal structures is the presence of microscopic pores or channels, where guest molecules can be located.

FMCs are attractive as fluorescent materials as they present the possibility of using inorganic and organic elements in fluorescence centres or to add phosphor molecules to the FMC structure as guests placing them into the pores. Results of studies using FMC in FCs are given in articles [53–56]. For the present, the highest quantum efficiency level of white FMC fluorescence was 0.2, reported in [56]. White fluorescence at UV excitation has become a result of the addition of matrix blue fluorescence with yellow fluorescence of an iridic system: $Ir(ppy)_2(bpy)]^+$ (*ppy* – 2-phenylpyridine, *bpy* – 2,2′- bipyridine) placed in the host pores. The quantum efficiency of the material fluorescence decreased by 10 % at 150 °C, which is an indicative of its high thermal stability. The photostability of the material was not reported.

4. CONCLUSION

1. At present, inorganic phosphorous is the only fluorescent material class successfully applied in FCs for BCs and UFCs in the field of illumination.

2. Among organic phosphors, polymeric phosphors are most likely to be used in future FCs.

3. An insurmountable obstacle for the use of molecular organic phosphor in FCs is the photo degradation of phosphors at comparatively high levels of absorbed energy, which increases with the influence of oxygen. Nevertheless, these materials are of interest for lighting engineering, for example, in decorative and design use and in outdoor light advertising.

4. The photochemical stability of new fluorescent materials, to which coordination compounds QP and FMC belong, is insufficiently understood and their prospects for application in FCs are not clear.

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ANALYSING CRITERIA FOR CHOOSING ENERGY EFFICIENT HIGH QUALITY LIGHT SOURCES AND LUMINAIRES

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ABSTRACT

The article analyses critera applying to the choice of energy efficient high quality light sources and luminaires, which are used in Russian domestic and international practice. It is found that national standards GOST P 54993–2012 and GOST P 54992–2012 contain outdated criteria for determining indices and classes of energy efficiency of light sources and luminaires. They are taken from the 1998 EU Directive #98/11/EU "Electric lamps", in which LED light sources and discharge lamps of high intensity were not included. A new Regulation of the European Union #874/2012/EU on energy labelling of electric lamps and luminaires, in which these light sources are taken into consideration, contains a new technique of determining classes of energy efficiency and new, higher classes are added. The article has carried out a comparison of calculations of the energy efficiency classes in accordance with GOST P 54993 and with Regulation #874/2012/EU, and it is found out that a calculation using GOST P 54993 gives underrated energy efficiency classes. This can lead to interdiction of export for certain light sources and luminaires, can discredit Russian domestic manufacturer light sources and does not correspond to the rules of the World Trade Organization (WTO)[1].

[1] At present, a draft of the Technical Regulations of the Customs Union "On informing consumers on energy efficiency of electric power-consuming devices", is in development, the basis of which is the Regulation of the European Union mentioned in this article (editor's note) .

Keywords: choice criteria of energy-effective and high-quality light sources, energy efficiency classes, engineering criteria, economic criteria

1. INTRODUCTION

There is a large number of LED light sources and luminaires of domestic and foreign production on the Russian market [1]. The technical specifications of many of these do not correspondent to the declared data and the requirements for energy efficiency and product quality. This means that sometimes uncertified products come to the market.

A wide choice of light sources and luminaires present a selection challenge for buyers. Various engineering and economic choice criteria for energy efficient and high-quality light sources and luminaires simplify the selection process.

2. A CHOICE CRITERION OF ENERGY EFFICIENT LIGHT SOURCES AND LUMINAIRES

The main selection criterion for energy efficiency of light sources and luminaires is their energy efficiency class (communicated via energy efficiency labelling).

Labelling energy efficiency is the main and most effective energy saving tool and a driving motive for decreasing the energy consumption capacity of the Gross National Product (GNP), as well as a stimulus for driving environmental improvements [2]. Energy efficiency equipment labelling is a method of classification and identification of product

Table 1. Energy efficiency classes of some LED light sources

Light source brand	Measured power, W	Actual luminous flux, lm	Energy efficiency class	
			According to GOST P 54993–2012	According to Regulation 874/2012/EU
IKEA	13.6	1121	A	*A*+
KOMTEX	9.34	912	A	*A*+
WOLTA	8.48	673	A	*A*+
Economica LED	11.12	815	A	*A*+
Elektromontazh	9.13	808	A	*A*+

within categories by power consumption their characteristics with the assignment of the corresponding label sign.

Power-consuming equipment is subject to energy efficiency labelling in more than 60 countries of the world [3]. The most complete penetration by this approach has occurred in the EU, where work on labelling began in 1992 after the adoption of Directive 92/75/EU.

The EU Electric lamps Directive 98/11/EU was published in 1998. It established seven classes of lamp energy efficiency (*A*, *B*, *C*, *D*, *E*, *F*, *G)*. Class A corresponds to maximum efficiency, and class G to minimum energy efficiency of lamps during operation. An energy efficiency class is determined by the energy efficiency index *EEI*, the calculating formulas for which are given in [4, 5].

Attempts to introduce energy efficiency labelling in Russia were made in the late 1990s. In 1999, three energy efficiency standards were issued. Unfortunately, these standards were not effective as implementation mechanisms for energy efficiency labelling were not developed and standard energy efficiency indicators of power-consuming equipment were not determined.

Work on energy efficiency labelling was started up again after the adoption of the Federal law #261-ФЗ [6]. Resolution of the Government of the Russian Federation #1221 of 12/31/2009 "On approval of the Rules of establishment of energy efficiency requirements of goods, works, services, which is commissioned to meet state and municipal needs" has confirmed a list of the goods, with reference to which requirements of energy efficiency are established. Light sources are included in this list.

Rules for determining the energy efficiency class of light sources by manufacturers and importers are stated in the Order of the Ministry of Industry and Trade of the Russian Federation #357 of 4/29/2010. These rules are taken entirely from Directive 98/11/EU. However, this Directive did not cover LED light sources and a number of high intensity discharge lamps.

Besides this Order, the mentioned rules are stated in the following standard documents: GOST P 54992–2012 and GOST P 54993–2012 [4, 5]. And GOST P 54993 establishes that it is also applicable to LED light sources.

Since 1998, there has been a rapid increase of light sources with a high luminous efficacy and especially of LED light sources. Therefore on 7/12/2012, the European Union adopted new Regulation #874/2012/EU on energy labelling of electric lamps and luminaires [7]. It covers requirements for incandescent lamps, fluorescent lamps, high intensity discharge lamps, LED lamps and LED modules. The scale of energy efficiency classes changed (*A* ++, *A*+, *A*, *B*, *C*, *D*, *E)*, and the formulae to determine energy efficiency indices also changed. Furthermore, an additional energy efficiency criterion – electric energy consumption by a light source – is introduced, measured in kW·h for 1000 h of its operation (W_c). Determination of energy efficiency indices is made according to the expressions given in [7].

Calculation of energy efficiency classes for the five best LED light sources with an E27 socle are given in Table 1 [1, Table 3]. The calculation is carried out in accordance with GOST P 54993 and according to EU Regulation #874/2012.

As can be seen from Table 1, calculation of an energy efficiency class according to the Russian standard documents gives underestimated results compared with Regulation 874/2012/EU. This can complicate export of Russian light sources and can discredit domestic manufacturers of the light sources.

3. ENGINEERING CRITERIA FOR CHOOSING HIGH-QUALITY LIGHT SOURCES AND LUMINAIRES

In work [1], an integral criterion to determine light source and luminaire quality is used:

$$K_0 = \frac{\Phi_v \cdot R_a \cdot \cos\varphi \cdot (100 - K_r)}{P \cdot T_{cc} \cdot C}, \qquad (1)$$

where Φ_v is luminous flux of the illumination device, lm; R_a is general colour rendering index; $\cos\varphi$ is power factor; K_r is ripple factor of the luminous flux, %; P is power consumption of the illumination device, W; T_{cc} is correlated colour temperature, K; C is lamp cost, rbl.

The following notes are important to mention together with this criterion:

1. It is not possible to mix engineering and economic criteria in one expression, because this can generate unexpected results. For example, work [1] drows the conclusion that "an analysis has shown that lamps with the best parameters are cheaper than lamps of poor quality", although it is well-known that a high-quality product is always more expensive than a product of poor quality.

2. This criterion cannot be applied to compare light emitting diodes of cold-white and warm-white light (i.e. with different T_{cc}) as their fields of application are different.

In [8], the requirements for lighting product energy efficiency and quality are offered together and two types of standard to be developed:

1. Minimum energy efficiency standards (*MEPS*);

2. High energy efficiency standards (*HEPS*).

Minimum energy efficiency standards will establish threshold levels for the technical (engineering) characteristics of light sources and luminaires.

Maximum energy efficiency standards should establish higher levels of energy efficiency for the development of new ambitious light sources and luminaires.

According to the authors, these standards should contain:

1. Requirements for energy efficiency of lamps and luminaires;

2. Requirements for operational characteristics of lamps and luminaires.

The energy efficiency requirements should correspond to international practice admitted in the World Trade Organisation (WTO), that is requirements for labelling of light sources and luminaires, and Regulation #847/2012/EU should be the source of the limits.

At the same time, it is important to consider the legal status of these standards. The law "On Technical Regulation" transferred all standards to the voluntary application category. In order to transfer the standard into the mandatory application category, it should be referred to in the Technical Regulation. For the fourteen years that the law "On Technical Regulation" has been in existence, no Technical Regulations containing lighting characteristics have been developed.

In EU countries, voluntary standards are also used but there are mandatory documents as well, which specify what standards are to be guided for. These are:

1. Regulations, which are completely mandatory and directly applied in all EU member states;

2. Directives, which are mandatory for EU member states, establishing the thresholds, which should be reflected in national laws.

These documents are confirmed by the European Parliament and by the EU Council. This type of technical regulation has allowed EU countries to achieve great successes in the promotion of energy efficient equipment, including in illumination system. For instance, from 2008 to 2013 the number of installed incandescent lamps was reduced 2.85 times, CFL number increased 1.6 times, and the number of LED lamps increased 72 times [9].

Taking into consideration the creation of the Customs Union and the complexity of standard documents and their agreement process between members of this Union, it is prudent to look to the experience of the EU. The practice of establishing energy efficiency requirements using Resolutions of the Russian Federation Government under the conditions of the Customs Union does not work as these Resolutions do not extend to other members of the Union.

Studies [10–12] show that all gas-discharge and LED light sources create higher current harmonics when operating. The greatest harmonics are created by compact fluorescent and LED light sources, which have no power factor correctors (PFC) in their control devices. An analysis of these tables [1] shows that most light sources present on the Russian market do not have PFC, i.e. they generate significantly high harmonics levels and have low power factors.

According to the Technical Regulation of the Customs Union TR CU020/2011 "Electromagnetic compatibility of technical facilities", all technical facilities generating electromagnetic noise should correspond to the electromagnetic compatibility standards. An evaluation of this correspondence is given in GOST P 56029–2014 [13].

The requirements for permissible level of higher current harmonics generated by light sources are stated in GOST 30804.3.2–2013 [14]. Operational characteristics of lamps and luminaires (along with Φ_v, R_a, $\cos\varphi$, K_p, P, T_{ct}, U_{rt} and energy efficiency class) need to be added, with information on how they meet the requirements of GOST 30804.3.2. In the EU, correspondence of light sources to the electromagnetic compatibility requirements is indicated by the sign. This sign is placed both on the packing of light sources and luminaires, and on light sources and luminaires themselves.

4. EVALUATION OF ECONOMIC EFFICIENCY OF INTRODUCING ENERGY EFFICIENT LIGHT SOURCES

When replacing light sources and luminaires with energy efficient devices, as well as evaluating their technical criteria, the analysis of economic efficiency of the replacement is important. When evaluating economic efficiency of introducing a new product, where there is a considerable difference in service life, the product service life cost (PSLC) technique is widely used in the international practice [15–18]. This approach allows selecting the most economic products with long service lifetimes.

According to GOST P 27.202–2012 [15], the PSLC evaluation is an economic analysis which determines the total cost of acquisition, possession and utilisation of a product.

Twenty years is the recommended life period used to determine PSLC value for illumination devices (ID) [16]. The service life includes the following stages:

– Acquisition;
– Installation and adjustment;
– Operation and maintenance;
– Charge-off and utilisation.

The cost of service life for the interval equal to an ID life time, can be determined by the formula [17, 18]:

$$PSLC = C_{acq} + \sum_{t=1}^{T} \left(O_t + \Delta K_t + U_t \right) \cdot \alpha_t, \tag{2}$$

where C_{acq} is ID cost connected with acquisition, installation and adjustment; O_t is annual operational expenses connected with cost of electricity, ΔK_t is the accompanying cost connected with replacement of the failed lamps; U_t is disposal value, i.e. utilisation cost of the failed lamps containing mercury; α_t is discount factor; T is life time period.

The discount factor is determined by the formula:

$$\alpha_t = \frac{1}{(1+r)^T}, \tag{3}$$

where r is a real interest profit rate, relative units:

$$r = \frac{E_{rt} - b}{1+b}, \tag{4}$$

E_{rt} is a rated discount rate, relative units; b – inflation level, relative units.

Annual operational expenses connected with the electricity cost are determined by the formula:

$$C_t = C_{ee} \cdot W_{ee}, \tag{5}$$

where C_{ee} *is* electricity cost during the initial stage, *rbl/kW·h*; W_{ee} is value of the consumed electricity per year, kW · h.

Accompanying annual expenses connected with the replacement of the failed lamps:

$$\Delta K_t = C_l \cdot N_l \cdot \frac{T_y}{T_{sl}}, \tag{6}$$

where C_l is cost of a lamp, rbl; N_l is number of lamps, pieces.; T_y is operating time of the illumination system per year, h; T_{sl} is standardised lifetime of a lamp, *h*.

Annual expenses for recycling and disposal of lamps containing mercury:

Table 2. Specific indicators of office IDs

Illumination device and lamp	Lamp		Luminaire		ID power (accounting for ballast losses), W	ID luminous flux, lm	ID life time, T_l, h
	Power, W	C_l Cost, roubles	Efficiency, %	C_{lu} Cost, roubles			
ЛВО10–4x18–021 *Rastr* and *T8 L 18/640 G13*	4x18	42.44	66	1968	86	3168	13000
ЛВО10–4x18–031 *Rastr* and *T8 L 18/840 G13 LUMILUX*	4x18	58.59	66	2094	79.2	3564	20000
ЛВО10–4x14–031 *Rastr HF* and *T5 FH 14/840 G5*	4x14	122.31	71	2405	61.6	3834	24000
ДВО11–42–001 *Frost* 840	–	–	–	6996	38	3712	50000

Note. LED luminaire is a non-demountable luminaire. When calculating, C_1 is accepted to be equal to C_{lu}

$$C_t = C_{\text{util}} \cdot N_1 \cdot \frac{T_{\text{y}}}{T_{\text{sl}}}, \qquad (7)$$

where C_{util} is cost of recycling and disposing of a lamp, rbl.

ID service life cost comparison criterion is the value of specific cost for one year of operation [19]:

$$\frac{PSLC}{T} = \frac{C_{acq} + \sum_{\text{t}=1}^{\text{T}} \left(O_{\text{t}} + \Delta K_{\text{t}} + U_{\text{t}}\right) \cdot \alpha_{\text{t}}}{T} \qquad (8)$$

As an example, a calculation of service life costs for the following IDs was carried out:

1) ЛВО10–4x18–021 luminaire manufactured by *Rastr* Company ACT3 OJSC with electromagnetic ballast and with fluorescent lamps *OSRAM T8 L 18/640 G13*;

2) ЛВО10–4x18–031 luminaire manufactured by *Rastr HF* Company ACT3 OJSC with electromagnetic ballast and with fluorescent lamps *OSRAM T8 L 18/840 G13 LUMILUX*;

3) ЛВО10–4x14–031 luminaire manufactured by *Rastr HF* Company ACT3 OJSC with electromagnetic ballast and with fluorescent lamps *OSRAM T5 FH 14/840 G5*;

4) ДВО11–42–001LED luminaire manufactured by *Frost* 840 Company ACT3 OJSC.

Characteristics of these IDs are given in Table 2. The data was sourced from the price-list and information from the ACT3 JSC official website as well as data from the Elektrik online store [21].

Using expressions (2) – (8) and characteristics given in Table 2, as well as varying number of operation hours of the illumination system per year, dependences of ID life service cost reduced to a year were obtained (Fig. 1). The cost of electricity is taken to be 5.04 rbl/kW·h (Nizhny Novgorod region), rated discount rate is equal to 15 %, inflation level is 5 % and 10 %. Cost of recycling and disposal for lamps containing mercury is taken to be 17 rbl/piece according to the price list of the company providing these services in N. Novgorod [22].

5. CONCLUSIONS

1. When choosing energy efficient and high-quality light sources, both technical and economic criteria should be considered.

2. To choose energy efficient light sources and luminaires according in line with international practice, it is necessary to use energy efficiency classes which meet international standards.

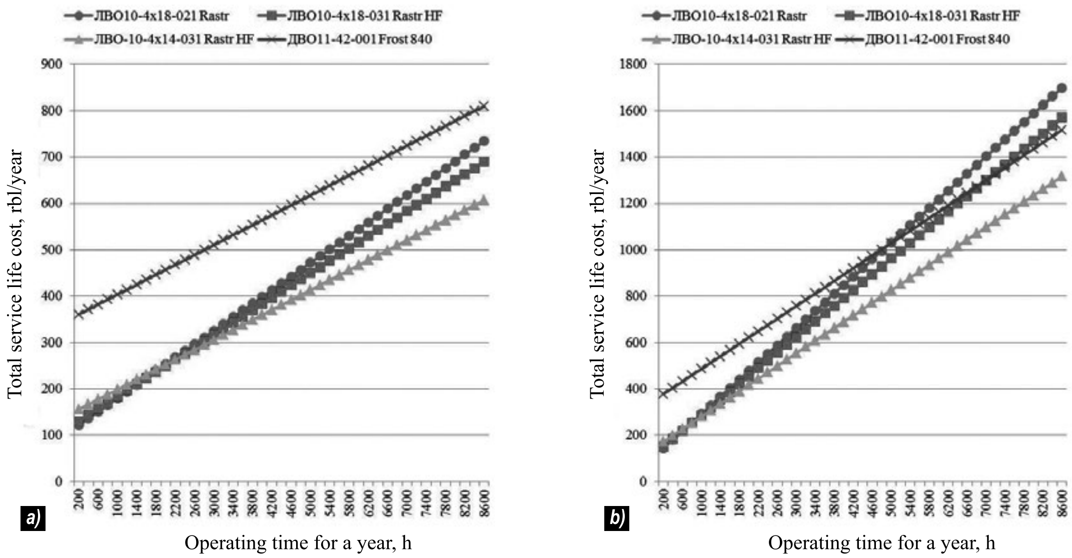

Fig. 1. ID service life cost: a) for inflation rate of 5 %, b) for inflation rate of 10 %

3. GOST P 54992–2012 and GOST P 54993–2012 should be revised as the use an outdated technique for the determination of light source and luminaire energy efficiency classes.

4. When selecting high-quality luminaires, apart from the main technical criteria given in GOST P 54350–2011, it is necessary to consider whether they meet the requirements for electromagnetic compatibility in the documentation submitted to the consumers.

5. As an economic criterion for energy efficient and high-quality light sources and luminaires selection, the *cost of service life* criterion is appropriate.

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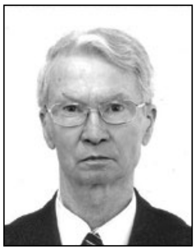

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MEASURING THE SEA WATER ABSORPTION FACTOR USING INTEGRATING SPHERE

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ABSTRACT

Practical questions of quickly determining the sea water absorption factor using an integrating sphere are considered: measurement technique and data processing, as well as reference solution calibration. Numerical experiments using the Monte-Carlo method are performed to evaluate the influence of the device features (absence of spherical symmetry and the presence of a reflection specular component from the quartz shell) on the determination of the absorption factor considering scattering properties of the medium. Examples of how the results of the proposed technique can be used are given under the conditions of sea expeditions.

Keywords: light absorption, integrating sphere, Monte-Carlo method, sea water

1. INTRODUCTION

The absorption factor is a key parameter determining the propagation of light radiation in the water medium including weakening flux of solar radiation with the increasing depth, the observation conditions and visibility range of underwater objects under natural and artificial illumination [1, 2]. However, for today determining the spectral absorption factor in a low-absorbing light-scattering medium, which sea water is for the most part in the visible spectrum, is a complex problem, generally because of the need to take scattering into account [3].

During the last two decades, *ICAM* (Integrated Cavity Absorption Meter) technologies, in which the studied natural water is placed within an integrating sphere [4–6], are developing rapidly. Such an approach allows avoiding problems connected with light scattering and makes it possible to increase the sensitivity due to multiple light reflections inside the sphere. However, to determine absorption factor absolute values, the effective span of photons in their multiple reflections should be known.

The idea of the integrating sphere method emerged in the 1950s and was implemented under laboratory conditions [7]. In the 1970s, theoretical and experimental studies of integrating spheres fully filled with absorbing and light-scattering mediums were undertaken at the VNISI [8]. Experimental device specimens for the separate measurement of the absorption factor and of the turbid medium scattering were created.

Within this article, the problem of determining absolute values of sea water absorption factor is considered, taking into account features of the portable spectrophotometer *ICAM* developed at the Chair of biophysics of the Biological department of the MSU [9]. These features are the absence of spherical symmetry and availability of reflection specula component connected with the quartz shell. By means of this device, measurements were performed under expedition conditions performed on samples of sea water in Baltic, Norwegian and Barents seas.

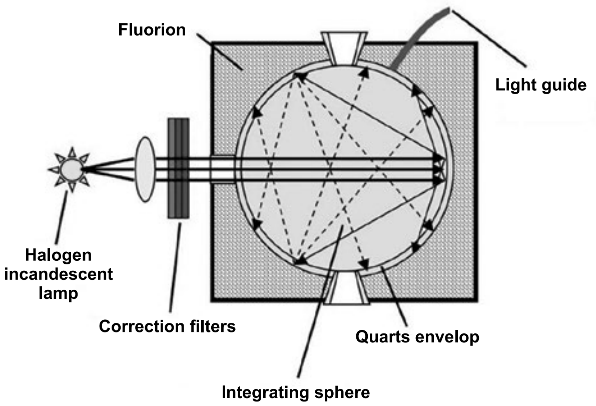

Fig. 1. Optical layout of the integrating sphere

The results of the application of the developed technique are reported in this article.

2. EQUIPMENT AND MEASUREMENT TECHNIQUE

2.1. *ICAM* spectrophotometer

An optical layout of the *ICAM* spectrophotometer is given in Fig. 1 [9]. The radiation source is a halogen incandescent lamp of 100 W stabilised by voltage. A collimated light beam passes through a combination of correcting colour light filters ПС-5, ПС-14 and СЗС-17, which partly level low luminous efficacy of the lamp in the blue and violet parts of the spectrum. After the light filters, the beam is directed to a spherical quartz envelope of 40 mm radius *R* and of 1.5 mm wall thickness placed into the integrating sphere made of fluorilon (*Fluorilon* 99-*W*™). The multiplied radiation scattered in the sphere goes out through a quartz light guide 600 µ in diameter to the *Ocean Optics USB4000* spectrometer. The light guide is built in the *ICAM* spectrophotometer housing at an angle of 110° relative to the axis of the specified light beam. Thus, the spectrometer records only multiple scattering undergone by the photons. Isotropy of multiple scattering allows avoiding its influence on the absorption level measurements (paragraph 3).

To determine the spectral absorption factor of sea water $a_{sw\lambda}$, values proportional to luminous fluxes leaving the sphere filled with sea water $I_{sw}(\lambda)$, empty sphere $I_s(\lambda)$, and sphere filled with distilled water $I_d(\lambda)$ are measured (hereinafter, "*value*" refers to intensity spectral concentration (ISC).

A reproducibility error in the measurement has two main reasons: time drift of the lamp luminance and dark noise of the spectrometer. Irremovable dark noise of the *Ocean Optics USB4000* spectrometer does not exceed 50 ISC conventional units at maximum measured ISC units of 63999. The measurement cycle takes about 15 min. (Fig. 2). During this time, ISC of the operation mode lamp decreases by approximately 175 units. The random error of the measurement is about 0.35 %.

2.2. Calibration

To determine the parameter values necessary to calculate the absorption factor from the measurement data, a calibration by brilliant green solution was performed. Measurement data using the *SPECORD M400* dual-beam spectrometer in configuration with troughs were used as a reference. The wavelength operational spectral interval of this device is (185–900) nm, wavelength error is ±0.3 nm, and the photometric resolution is ±0.003 absorption units (ABS) at *ABS* < 1.

To prepare the solution, clear water obtained by inverse osmotic filtration was used. The concentration of the solution was selected so that sufficient dye absorption measurement accuracy would be provided on the one hand, and only one-fold scattering would occur, on the other hand. The measurements were carried out according to the dual-beam principle: a trough with clear water was placed into the reference channel. And into the re-

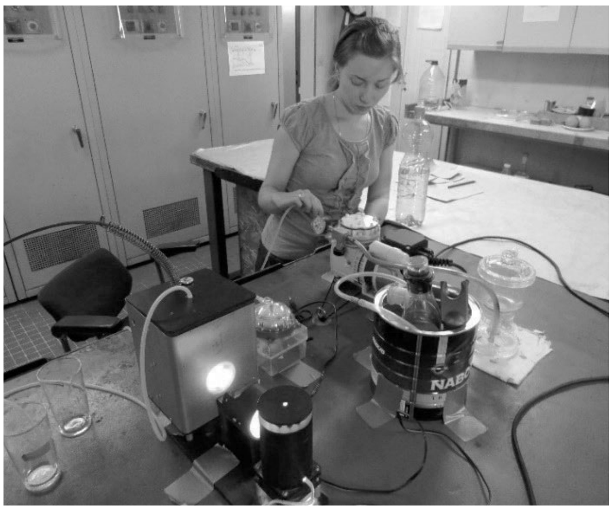

Fig. 2. Measurements of sea water absorption factor in a shipboard laboratory (a marine expedition, July, 2016); bottom left is the *ICAM* spectrophotometer, on the right is the filtration installation

ference channel, a trough with water was placed to obtain the baseline first, and then brilliant green solution was added. The water was allowed to settle for some time to allow gas bubbles, which could strengthen scattering, to escape. Brilliant green fluoresces at $\lambda_{max} \approx 660$ nm [10], which coincides with an abrupt decrease of absorption. Therefore fluorescence was not observed.

The absorption spectrum of brilliant green was calculated by the formula:

$$a_{gr\lambda} = \frac{1}{l}\left(ln\frac{I_0^{Sp}(\lambda)}{I_{gr}^{Sp}(\lambda)}\right), \quad (1)$$

where $a_{gr\lambda}$ is the spectral absorption factor of brilliant green, $l = 0.05$ m is the trough length, $I_0^{Sp}(\lambda)$ is ISC when measuring the baseline (when both troughs are filled with distilled water), $I_{gr}^{Sp}(\lambda)$ is ISC when measuring with the brilliant green calibration solution.

The measurements were performed by five spectra series, in two cycles; then the results were averaged. Optical concentration measurement error using the *SPECORD M400* spectrometer is 0.3 %, which taking into account the trough length, gives a measurement error $a_\lambda = 0.06$ m^{-1}.

3. SIMULATION OF LIGHT PROPAGATION IN THE INTEGRATING SPHERE BY MEANS OF THE MONTE-CARLO METHOD

The $I_{sw}(\lambda)/I_s(\lambda)$ relationship (paragraph 2.1) does not only depend on the spectral absorption factor a_λ but also on inner surface spectral reflection factors $\rho_{sw\lambda}$ and $\rho_{s\lambda}$. For the real *ICAM* device, these parameters depend on the sphere inner shell boundary refractive indices (sea water – quartz and quartz – fluorilon), on the thickness of the quartz envelope wall, on the outlet diameter and position, as well as on the reflective properties of the fluorilon. To evaluate the influence of these parameters, a simulation of light propagation in the *ICAM* was performed using the Monte-Carlo method. Direct (analogue) simulation, which is the simplest version of this method, was used [11, 12].

For each photon, processes of absorption and scattering in the medium, refraction and reflection on the boundaries quartz – sphere interior and quartz – fluorilon, absorption in fluorilon, and output from the sphere through the light guide were simulated.

3.1. Numerical experiments and interpolation formula

Simulation calculations with different values of the listed *ICAM* parameters under the condition $a_\lambda R \leq 0.1$, showed that in all cases results for the relationship $f(a_\lambda) = I(\lambda)/I_o(\lambda)$, where and input and output ISCs obtained by the Monte-Carlo method with good accuracy are approximated by the formula:

$$f(a_\lambda) = k/(1+ua_\lambda)^v, \quad (2)$$

where $k = f(0)$, as well as u and v parameters are customised in accordance with the calculation results by the least square method. Previously, a similar formula with small differences was used in work [13].

For all performed calculations, the root-mean-square error according to formula (2) did not exceed the Monte-Carlo method error. The performed calculations showed that their relative error was about 10^{-3}.

3.1.1. Effect of medium scattering properties

One of the most important questions is how far the assumption of the independence of the (a_λ) function from the scattering properties of the medium filling the sphere can be applied. As shown in studies [4, 5], for a spherically symmetric system with Lambert wall reflection, this assumption is used with good levels of accuracy. Strictly speaking, the system in our case is not spherically symmetric, and reflection from the surface with a quartz shell is not quite Lambert, even if we take the reflection from the fluorilon to be Lambert. For this purpose, simulating calculations were performed for an integrating sphere without a quartz shell under the assumption that the inner surface reflection contains a specula component, and the medium filling the sphere is scattering.

For the scattering simulation, the Henyey-Greenstein indicatrix and scattering factor of the studied medium (see below) were used. The surface reflection was simulated using the function:

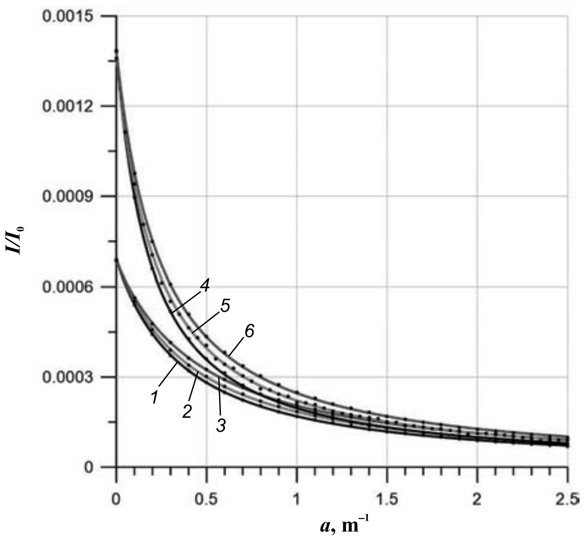

Fig. 3. Comparison of the calculated results with various reflection factor and relative refractive index values of fluorilon:
1, 2, 3 – $\rho_s = 0.98$; *4, 5, 6* – $\rho_s = 0.99$; *1,4* – $n_w = n_f = n_q$; *2, 5* – $n_w = 1.34$, $n_q = 1.45$, $n_f = 1.35$; *3, 6* – $n_w = 1.34$, $n_q = n_f = 1.45$. Solid lines show the calculation according to formula (1), points show the calculation according to the Monte-Carlo method

$$r(\mu_r,\phi_r;\mu_i,\phi_i) = \\ = \rho_s\left\{p\delta(\mu_i+\mu_r)\delta(\phi_r-\phi_i)+(1-p)\mu_i/\pi\right\}, \quad (3)$$

where μ_i and μ_r are cosines of zenith angles of incident and reflected rays, φ_i and φ_r are correspondent azimuthal angles, δ is Dirac function, p is a relative part of the specula component. The first expression in the curly brackets describes specula reflection, and the second relates to Lambert. The simulation was carried out in a wide parameter interval: the scattering factor is 0 and 5 m^{-1}, average scattering angle cosine is 0 and 0.9 and the absorption factor is from 0 to 2.5 m^{-1}.

The calculation for $p = 0.1$ showed a negligible influence of the medium scattering properties; scattering influence becomes significant only for $p \geq 0.5$.

To check the assumption of the *f(a$_\lambda$)* function's independence on the medium's scattering properties, calculations were made for an integrating sphere with a quartz shell 1.5 mm in thickness (paragraph 2.1).

The calculation results showed that the contribution of the specula component when reflecting at the boundaries is not significant, and the assumption that the results of the absorption factor measurement are independent from the scattering parameters can be considered to be reasonable.

3.1.2. Influence of Freshnel refraction and reflection

Let's consider the possibility of simply taking accounting for Fresnel refraction and reflection from the sphere inner surface (the studied medium is quartz and quartz – fluorilon), and its influence on the measurement results using the *ICAM* spectrophotometer. In other words, whether is it possible for each set of permissible refractive indices to introduce a concept of a surface effective reflection factor so that formula (2) would essentially become one-parametric.

The dependences of the calculated result on relative refractive indices (RRI) of water, quartz and fluorilon are shown in Fig. 3.

It can be seen from Fig. 3 that the dependence of the *f(a$_\lambda$)* function, namely *u* and *v* parameters in formula (2), on the *RRI* is considerable. Parameter *k*, i.e. *f(0),* only depends on spectral reflection factor of the fluorilon $\rho_{s\lambda}$, whereas at $a_\lambda > 1$, refraction influence can be more essential than fluorilon reflection.

3.2. Calculation formulas

The spectral dependence of the absorption factor for the studied liquid is obtained by transforming formula (1): $a_\lambda = \left\{\left[kI_0(\lambda)/I(\lambda)\right]^{1/v} - 1\right\}/u$, contains an input ISC $I_o(\lambda)$. In order to exclude this value, measurements were taken with the empty sphere, for which equality $I_s(\lambda) = k_s I_o(\lambda)$ is correct. It follows here from:

$$a_\lambda = \left\{\left[\left(k/k_s\right)I_s(\lambda)/I(\lambda)\right]^{1/v} - 1\right\}/u, \quad (4)$$

where *I* is spectral dependence of the signal for the studied water solution (in particular, sea water), *k* is the coefficient for a liquid with water's refractive index.

Another calibration method of the *ICAM* spectrophotometer is based on using a water solution with the same refractive index as sea water and with a known absorption factor. For example, one

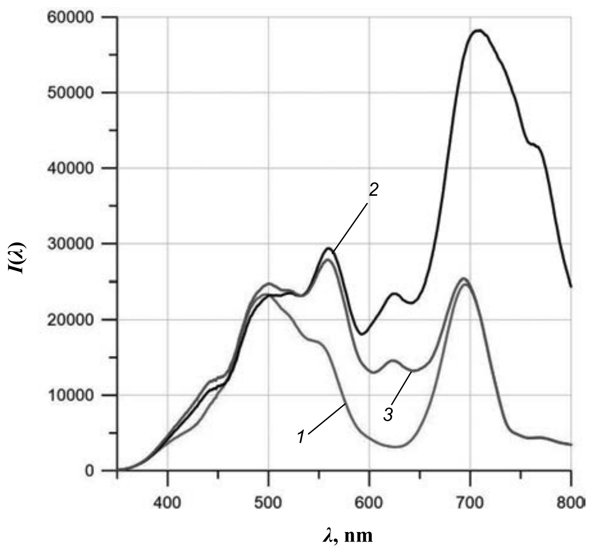

Fig. 4. Experimental results with the dye solution (1), empty sphere (2), and distillate (3)

can use clear (pure) water, for which spectral dependence $a_{d\lambda}$ is known [14].

In this case k is not a part of the calculation formula:

$$a_{sw\lambda} = \left\{\left[I_d(\lambda) / I_{sw}(\lambda)\right]^{1/v} \times \left(1 + u a_{d\lambda}\right) - 1\right\} / u, \qquad (5)$$

where (paragraph 2.1) $I_d(\lambda)$ is the ISC measured in the experiment with a reference solution (distillate).

3.2.1. An experiment with brilliant green dye

Parameters k, k_s, u, and v in formulas (4) and (5) can be calculated using the Monte-Carlo method, if *ICAM* parameters are known. However, not all these parameters are known, especially in respect to the fluorilon reflection factor and refractive index. To customise these parameters, an experiment with brilliant green and a *SPECORD* device (paragraph 2.2) was performed.

In the brilliant green experiment, $a_{gr\lambda}$ are known. These are the dye's spectral absorption factors measured by the *SPECORD* device. $I_{gr}(\lambda)$), $I_d(\lambda)$) and $I_s(\lambda)$) are ISCs in the experiments with the dye solution, distillate and empty sphere respectively (Fig. 4).

To calibrate the device, k parameters were computed ($0.76 \cdot 10^{-3}$), *u (1.911)* and *v (1.27)* assuming that RRI values are $n_w = 1{,}34$, $n_q = 1{,}45$ and $n_f = 1{,}45$.

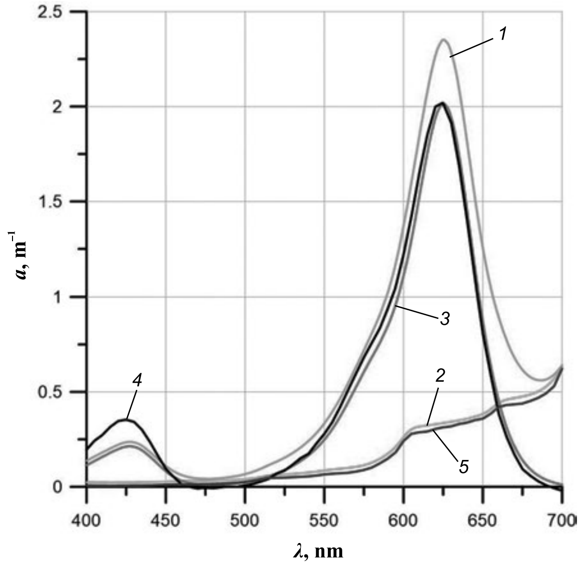

Fig. 5. Absorption spectra computed according to the experiment data with the dye:
1 – dye solution; *2* – distillate; *3* – dye (according to the *ICAM* indications); *4* – dye (according to the *SPECORD* indications); *5* – clear water according to data [13]

The value of parameter k_s is selected to be $0.66 \cdot 10^{-3}$ from the condition that a_λ values computed according to (4) coincide with the values measured by the *SPECORD* device, and a_λ of the distillate ($a_{d\lambda}$) is positive and differs from the work [13] data inessential.

Values $a_{gr\lambda}$ and $a_{d\lambda}$ were calculated by formula (4), and in doing so, $a_{gr\lambda} = a_{sol\lambda} - a_{d\lambda}$, where $a_{sol\lambda}$ is a_λ of the dye solution. The calculation results are presented in Fig. 5.

Absolute error of a_λ according to our evaluations is 0.05–0.06 m^{-1} and depends mainly on the measurement errors.

4. RESULTS OF EXPERIMENTAL MEASUREMENTS

Measurements of sea water a_λ ($a_{sw\lambda}$ were performed using the *ICAM* spectrophotometer during a trip of the Academician Mstislav Keldysh research vessel from Kaliningrad to Arkhangelsk between June 29 and July 9 2016. The obtained results are presented in Fig. 6. As it can be seen, at the research posts in the Baltic Sea, absorption factor values are significantly higher than in the Norwegian and Barents seas. In Fig. 6b, examples are given of the measured a_λ of the particles suspended in water, which are calculated as a difference of the measured $a_{sw\lambda}$ values before and after sea water filtration using a filter with a pore size of 0.4 μ.

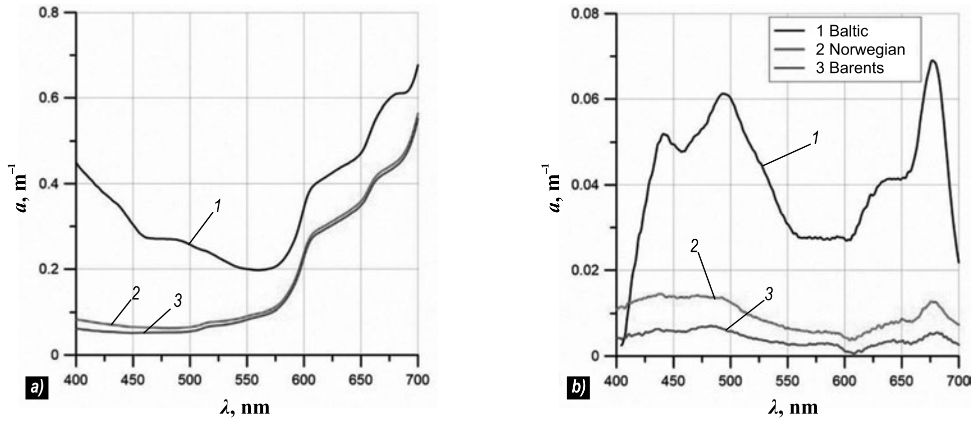

Fig. 6. Absorption spectra of sea water (a) and of particles (b) (Baltic, Norwegian and Barents seas, June and July 2016)

Curve $a_{sw\lambda}$ for the Baltic Sea is of interest due to the fact that blossoming blue-green algae (cyanobacteria) are visible. This presents as a peak corresponding to absorption in a wide band with λ_{max} of about 620 nm, which is of phycocyanin – the pigment marker of cyanobacteria, and λ_{max} of about 675 nm corresponds to the absorption band for chlorophyll *a*, which is a photosynthesizing pigment. These results are consistent with direct tests for phytoplankton species composition performed later in the laboratory. Such results are absent from the absorption spectra in the Norwegian and Barents seas.

5. CONCLUSION

The proposed technique allows to quickly determine the absorption spectra of sea water ($a_{sw\lambda}$) by means of an *ICAM* spectrophotometer under marine expedition conditions. Two measurements are needed: with a sphere filled with sea water, and with an empty sphere.

Prior to the measurement, a single calibration of the device using a reference water solution should be performed.

The Monte-Carlo method calculations carried out showed that despite the lack of spherical symmetry in the used device and the presence of a specula component due to the quartz shell, the independence of $a_{sw\lambda}$ results from the medium scattering properties remains when changing the scattering factor from 0 to 5 m^{-1}.

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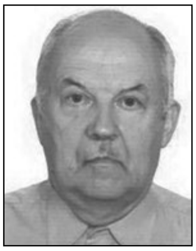

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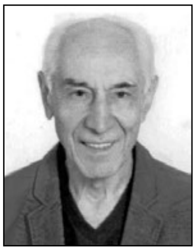

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NIGHT SKY BACKGROUND BRIGHTNESS ESTIMATION BY THE EXAMPLE OF THE ST. PETERSBURG CITY

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ABSTRACT

Within the big city boundaries, artificial component of the sky glow increases every year. The main reasons are the expansion of the cities, the rapid growth of technical capabilities, inefficient lighting design without master-planning and lack of quality control of lighting projects. The data of astronomical observations confirm a significant brightness increasing in the lower atmosphere due to factors of terrestrial origin. The problem is mostly acute for observatories are located near major cities, which are struggling for the possibility of further research. Night sky background glow estimation is an actual direction for research in the modern world. The paper considers a model for calculating the sky brightness for the St. Petersburg city. According to the developed model observation position is located near the Pulkovo Observatory. The model is based on the Garstang's method with use of Python programming language.

Keywords: sky glow, sky brightness, background brightness

1. INTRODUCTION

Night sky artificial glow increases due to the diffuse scattering of artificial light on the components of the lower atmosphere: the vapours of water and particles of dust.

For the first time, the brightness of the lower atmosphere was assessed by the staff of the Department of Physics and Astronomy at the Padua University of Italy. P. Cinzano, F. Falchi and C.D. Elvidge, being concerned about the growth rates of the night sky glow, developed the first atlas using data obtained via satellites intended for meteorological research [1].

In addition to experimental astronomical studies, modelling of the corresponding conditions is used to estimate the artificial component of the sky glow. The most simplified model for estimating sky glow is the Walker's model [2], which takes into account the population size and remoteness of the observer from the city centre.

More complicated model, taking into account the approximation for small angles with allowance for the particle scattering mechanisms, was proposed by Bertiau and Treanor [3]. The assumptions adopted in the model are homogeneity of the atmosphere composition; directivity of scattering of aerosol particles in the visible part of the spectrum.

The Treanor's model was modified by Garstang [4], taking into account the heterogeneity of the atmosphere. In the modified methodology was taken into account the exponential characteristic curve of particles density depending on the height.

The Garstang model has been responsive to several thousand American observatories, such as Mount Wilson, the Lick Observatory, the Palomar Observatory, Kitt Peak National Observatory, Sacramento Peak, Mauna Kea, McDonald Observatory [5] and still widely uses in different research studies [6,7,8].

The aim of the study was night sky background glow estimation with use of the Garstang's model, modified for the St. Petersburg city, taking into account the population of 18 districts of the city accor-

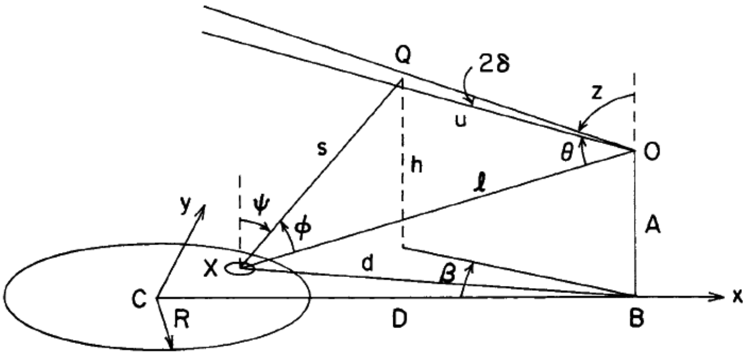

Fig. 1. Schematic representation of the light propagation from the side of the city to the observer; radiation from the element *dx* · *dy* in point *X* with coordinates (*x*, *y*) reaches the observer in point O, [4]

ding to Petrostat data and taking into account technical data about the luminaries according to State Unitary Enterprise "Lensvet".

2. METHODOLOGY

The model was developed using the programming language Python 3 with connecting libraries *numpy, sympy, sympy.plotting* in the Jupiter Notebook development environment. *NumPy* is a library of high-level mathematical functions with the ability to support large multidimensional arrays. *SymPy* is an actively developing library for character calculations.

According to developed model, the observation point (p.O) was considered near the oldest Russian observatory called Pulkovo, which is located at Pulkovo Heights, 75 metres above sea level. The distance from each of the city district to the point of observation does not exceed 50 km, so the curvature of the Earth's surface was not taken into account, Fig 1.

The value of the natural glow contribution for clear sky was taken into account in case of the artificial light absence with minimal solar activity, about 0.00017 cd/m^2.

The model includes Rayleigh scattering characteristic of atmospheric molecules with a cross section $\sigma_R = 4{,}6 \times 10^{-27}\,\text{sm}^2$ at a wavelength 550 nm, multiple scattering of molecules and aerosol particles, absorption in the lower layers of the atmosphere for the vertical propagation of particles in accordance with the Beer–Lambert Law, Fig.2.

The model contains the following assumptions:

- The molecules are in hydrostatic equilibrium,
- The aerosol density is an exponential function,
- The atmosphere is uniform horizontally.

The distribution of lighting intensity in the upper hemisphere, according to the model, was estimated by the formula [11]:

$$I_{up} = \frac{LP}{2\pi} \times \\ \times \left\{2G(1-F)\cdot cos\psi + 0{,}554\cdot F\cdot\psi\right\}, \quad (1)$$

where *G* is the albedo of the surface, *F* is the fraction of the luminous flux emitted by the luminaires in the upper hemisphere, *P* is the population, *L* is the luminous flux per capita.

The basic equation of the sky brightness model [9]:

$$b = \pi\cdot I_{up}(\psi)\cdot S^{-2} \times \\ \times \int du\cdot e^{-\tau(s)}\cdot(1+SAA)\cdot e^{-\tau(s)}. \quad (2)$$

Based on the statistical data of the State Unitary Enterprise "Lensvet" and on data of the population of Petrostat [10], the average luminous flux per capita was estimated as 670 lm. For each region, the total average luminous flux was calculated taking into account the population. The albedo of the earth's surface was taken equal to 0.15, luminous flux fraction emitted by the luminaires to the upper hemisphere was taken equal to 0.13. Based on the Garstang's model, night sky luminance was estimated with the natural glow considered as 0.00017 cd/m^2.

For each of the 18 city regions, there was estimated the intensity of the radiation to the upper hemisphere for different values of the zenith angle, z = 0 ° and z = 45 °.

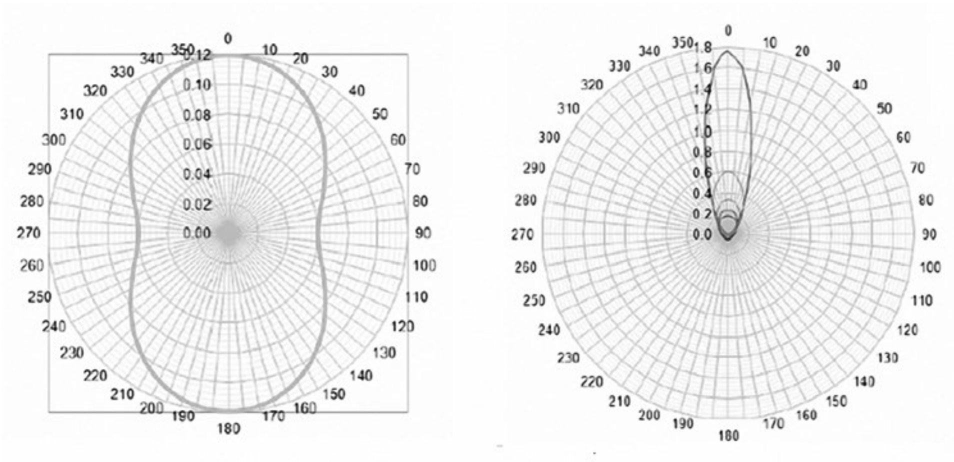

Fig. 2. Scattering diagrams of the molecular components of the atmosphere (left) and aerosol particles (right)

The value of average luminance, taking into account 18 regions: for observing direction 45 ° towards the city is equal to 0.17 cd/m^2; while observing 0 ° toward the city – 0.21 cd cd/m^2, which correlates with the data of ground-based experiments provided by Pulkovo Observatory for a clear sky on a moonless night with low solar activity.

3. ANALYSIS

According to the data of the Pulkovo Observatory, luminance of the objects under study varies from 0.017 to 43000 cd/m^2 in the transition from the astronomical system of magnitudes to lighting units. At the same time, luminance of 1700 objects of observation is relatively low and amounts to (0.0017–1.7) cd/m^2. Thus, 15 % of the objects are in potential danger from the point of view of the possibility of carrying out measurements. There are satellites of Uranus, asteroids, parallaxes, stars with a suspected invisible component among the objects in the risk zone.

Researches of further interest taking into account obtained results:

• Finalization of the model and program code, taking into account the forecasting of the impact of new construction near the observatory;

• Modification of the model and program code taking into account the influence of different weather conditions;

• The more detailed accounting of changes in the natural glow of the sky during the year;

• Analysis of the spectral composition of the radiation influence;

• Comparison of results obtained by modelling with experimental data;

• Exploring the possibilities of night sky glow decrement by implementing control systems.

4. DISCUSSION

The issue of reducing the background component of night sky glow and assessing the degree of its influence both on human life and on the accuracy of astronomical observations is topical, but in Russia at the moment is not sufficiently studied. Currently, environmental laws that affect on the night sky glow decrement exist only in five countries around the world. In a number of countries, there were developed recommendations for lighting designers, aimed at rationalizing of lighting solutions.

From the point of view of lighting design to reduce the dynamics of sky glow increasing, it is necessary to take into account the patterns of light propagation in the lower atmosphere and the nature of scattering by various particles in its composition, as well as the introduction of control systems for outdoor lighting to reduce the brightness levels of illuminated surfaces at night.

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THE INFLUENCE OF THE LIGHT SCENARIO DRAMATURGY ON RESTORATIVE QUALITY OF AUDIO-VISUAL ENVIRONMENT STIMULATION

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ABSTRACT

The article applies to the development and expansion of the opportunities inherent in the non-pharmacological medicine, namely, to reduce stress and increase the productivity of the labour. It considers drama basis influence on audio-visual stimulation effectiveness. This kind of stimulation improves working performance and capacity. The group of 40 people was taken as a model. The effectiveness of a dramatic basis in creating an audio-visual environment showed a 38 % increase in comparison with the usual approach.

Keywords: psychological health, working capasity increase, stress reduction, art therapy, audio visual stimulation, restorative environment

1. INTRODUCTION

Continuous search for new means and methods of stress reduction (including stress in the workplace), productivity-enhancing activities and improvement of psycho-emotional health and quality of living is characterizing the reality [1, 2].

Artistic activity is one of the trends in this area. Scientific studies in this area show a positive impact on human condition from art classes and visits to museums and theatres [3].

Lux Aeterna Theatre sound and light performances have been suggested as a base to develop means of stress reduction and productivity increase [4]. The research results confirmed positive impact of a light and music performance piece on change in voluntary attention, rate of psychomotor activity and resistance to monotonous activities that require constant concentration.

The purpose of this study was to determine the effect on drama base session efficiency, based on which audio-visual content is modelled. Drama (scenario, libretto of consistent development and interaction of abstract light and sound images) is transformed into light and sound score. The for-

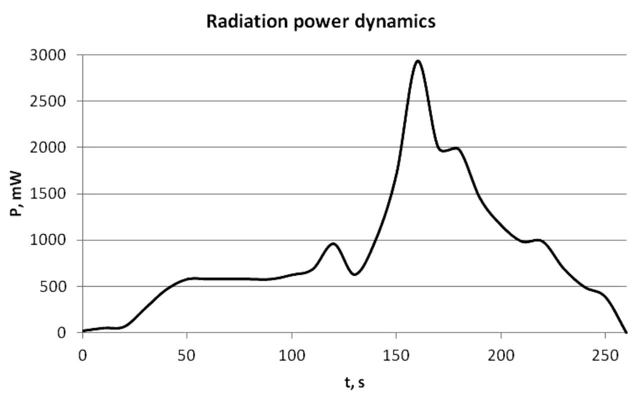

Fig. 1. Dynamics of laser radiation power at session

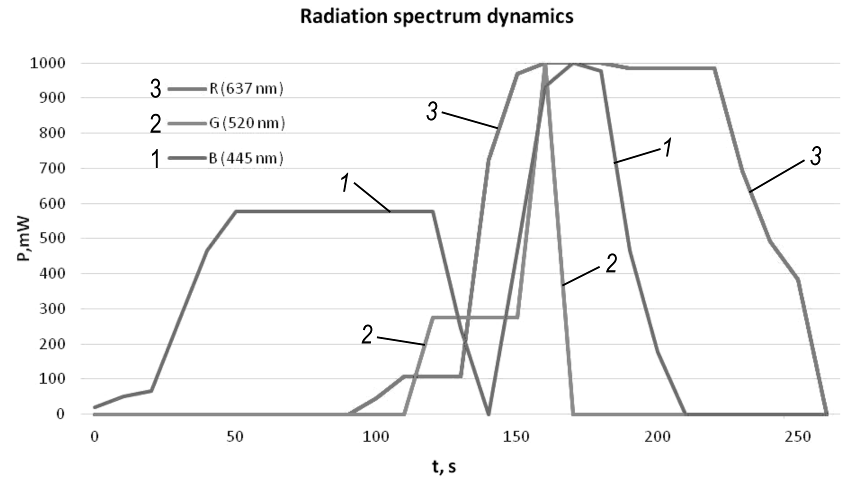

Fig. 2. Dynamics of radiation spectrum of the original piece

mation of the light image is influenced by the light form, the dynamics of the radiation power, and the dynamics of the radiation spectrum.

2. DESCRIPTION OF THE EXPERIMENT

Four types of audio-visual content were prepared for the experiment. Dynamics of laser power during the session is presented in Fig.1 and is the same for all four content types. The content of the first type is the original piece from "Gravitation Zero" performance by Lux Aeterna Theatre, with duration of 260 seconds. Dynamics of light emission spectrum change according to the score, Fig. 2. Three remaining contents have the same music piece, with similar dynamics of radiation power presented in Fig. 1, but with monochromatic radiation at wavelengths of 445, 520, 637 nm, respectively for each type.

40 students (aged 19–23 years, students of ITMO University, 50 % female) took part in the experiment. The participants were divided into four focus groups. A respondent took a test based on Landolt's rings method, then was subjected to audio-visual effects and took the test again. The Landolt's rings test is well established in numerous studies to determine the impact of lighting conditions on productivity [5].

3. METHODS

Each respondent took the test based on Landolt's rings before and after viewing the audio-visual content. A chart, which is presented in Fig. 3, was shown to subjects on the monitor screen while testing. The symbol size corresponded to 14 PT. A respondent had to click the mouse to mark particularly oriented symbols. 5 minutes were given for one test, after each minute a respondent could take a break. The results counted the number of symbols that has been reviewed and the number of errors. Two kinds of errors were considered: skipping of the specified symbol and marking the incorrect symbol. As a result, productivity was estimated by the formula:

$$S = \frac{N}{2} - \frac{2.8n}{60}, \quad (1)$$

where S is productivity index,

N is the number of viewed symbols, characterizes speed of information processing,

n is the total number of errors, characterizes accuracy.

To assess exposure results, average group values of productivity "before" and "after" audio-visual session S_1 and S_2, respectively, were used, as well as the index changes, Eq. 2:

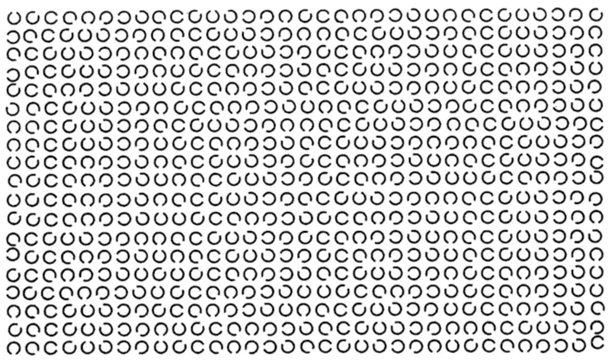

Fig. 3. Test table of Landolt's correction samples

Table 1. *p*-level value by Wilcoxon test.

Dynamics of spectrum change	n_{cp}	SD_n	p	N_{cp}	SD_N	P
Original scenario	0.865	0.016	0.08	1.541	0.049	0.09
Without dynamics, λ=445 нм	0.925	0.021	0.08	2.136	0.093	0.09
Without dynamics, λ=520 нм	0.909	0.032	0.11	1.844	0.106	0.12
Without dynamics, λ=637 нм	0.918	0.016	0.08	1.859	0.121	0.10

Table 2. Indicators for different content type

Dynamics of spectrum change	Δn_{cp}	ΔN_{cp}	ΔS_{cp}
Original scenario	-2 %	10 %	11 %
Without dynamics, λ=445 нм	-2 %	6 %	8 %
Without dynamics, λ=520 нм	-3 %	-1 %	0 %
Without dynamics, λ=637 нм	0 %	5 %	5 %

$$\Delta S = \frac{S_2 - S_1}{S_1} \times 100, \%. \qquad (2)$$

4. RESULTS AND DISCUSSION

The statistical reliability of the results of the experiments was determined by Wilcoxon signed-rank test [8] with the help of SPSS Statistics. Shift values were calculated and ranked, p-level values for the number of the reviewed symbols and the total number of errors for each focus group were determined. Average values, average error of the original parameters and *p*-level values are presented in Table 1. The minimum *p*-level value is p=0.12.

Table 2 presents average values of changes in such indexes as accuracy, speed of information processing and average change of productivity index based on the above mentioned indexes for each content type.

Various studies [6, 7] characterize colour effect:

• Blue is recommended for monotonous work, concentrating \ dark blue scatters attention and relaxes;

• Green promotes mental activity, allows focusing and calms;

• Red increases productivity and creativity after brief exposure.

The results of Landolt's correction samples generally correspond to those descriptions, the effects of the scenarios can be described as follows:

• Scenario at the wavelength of 445 nm increases accuracy of task performance (Δn is negative, the number of errors is reduced), speed of information processing simultaneously increases;

• Scenario at the wavelength of 520 nm improves performance accuracy, concentration to a greater degree, thus speed of information processing decreases;

• Scenario at the wavelength of 637 nm does not affect accuracy, but increases the processing speed.

Therefore, accuracy of information processing characterizes focusing and concentration, while information processing speed characterizes performance. The relaxation effect can be of two types: moderate in case of 445 nm scenario, the result is recuperation and increased performance increment; and strong, in case of 520 nm scenario, resulting in performance decrease. Reverse activation mechanism in case of 637 nm scenario shows increased efficiency almost equivalent to 445 nm scenario. The 445 and 520 nm scenarios have approximately the same increase in concentration. The 637 nm scenario does not affect it.

The highest rates are observed in the original scenario, which presents all wavelengths on drama basis. Its efficiency is 38 % higher than in monochromatic scenario at the wavelength of 445 nm.

The energy ratio for the entire duration of the original scenario are at wavelengths 445nm, 520nm, 637nm are equal to 44 %, 9 %, and 47 % respectively. Relation of radiation proportions at different wavelengths and the total effect, which is expressed in figures, is not possible to state in the experiment. So, for performance rate the total effect is calculated by direct summary of values for each wavelength, while for the accuracy rate the value remains unchanged. These relationships require comparison of different complex scenarios.

5. CONCLUSION

The conducted studies have shown effectiveness of audio-visual means to improve efficiency when performing repetitive work, that require high level of concentration (a session, that lasts less than 5 minutes, increases productivity by more than 10 %). Thus, accuracy and execution speed are increasing.

Drama based content ensures greater effect of attention restoration. The original piece of the Lux Aeterna Theatre performance, where visual score has complex pattern of wavelength change, leads to increase in productivity in 1.3–2.2 times, than the monochrome scenarios for the same duration.

Further studies should be aimed on establishing the nature of relations between proportions of radiation at different wavelengths, sequence and dynamics of their development during the scenario, and optimal session duration, and duration of positive effects after viewing.

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SPACE AND TIME OF LIGHTING DESIGN: THE RESULTS OF THE INTERNATIONAL RESEARCH-TO-PRACTICE CONFERENCE "LIGHTING DESIGN – 2016"

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ABSTRACT

The paper is an overview of the main discussion areas of the International Research-to-Practice Conference "Lighting design-2016". The theme of the year 2016 was devoted to "Light, Space, and Time". Professional design community, scientists, architects, artists, engineers, representatives of media and IT-technologies from nine countries including Russia discussed the issues related to art and science integration, urban lighting environment, technical culture and new technologies, education in the field of lighting design.

Keywords: conference, lighting design, lighting environment, urban space, people

International Research-to-Practice Conference "Lighting design", annually held by ITMO University, CLD ITMO University and Creative Association of Lighting Designers RULD, is a discussion platform of a new type, based on multi-level integration principle.

A system of flexible vertical (between different fields, areas of knowledge, etc.) and horizontal (various dimensions, angles, etc. within one field or problem area) links and relations are based on this principle. Conference theme, which changes annually in accordance with current issues and priorities of lighting design, provides unity of this mobile structure.

Through this approach, the conference forms active environment, where fundamental and applied research complement one another; and such areas, as science and art, design and psychology, business and technology interact, creating new intersection points of different fields of knowledge and practical experience.

The theme of the conference in 2016 proved to be quite variable and plastic to combine different interests and points of view to be discussed, and yet very specific to clearly define problematic areas of the conference. The observed diversity of opinions, approaches, author's positions (35 speakers, including 9 foreign headliners), number of participants (390 guests from 9 countries including Russia) confirm, that the proposed topic is equally relevant to the professional design community, scientists, architects, artists, engineers, media business and IT-technologies representatives (24 reports and workshops).

Four areas distinguished the most: art & science, urban lighting environment, technical culture and new technologies, lighting design and education. Within these areas the following issues were discussed:

– Light as a fast and effective tool for idea generation and innovation;
– The role of humanities in new technologies;
– Investment prospects of the XXI century;
– Contemporary lighting culture specifics and formation of social demand for high-quality public spaces;
– Education and professional training of exclusive specialists.

ART & SCIENCE

Art & Science is one of prospective areas in search for a new strategy of society development and ways of interaction between a man and technology. Science enables to "define a field and work in new areas", whereas art "allows you to look above these areas and intuitively identify trends for science in future". These are the prospects of integration of these two important spheres of human activity, according to the conference participants [1, p. 30]. Widespread use of portable electronics and its impact on social processes; experimental models created with the help of IT, media, robotics and photonics; new multimedia and interactive forms of human interaction with artificial light; multimedia training simulators – all these trends are rapidly changing marketplace of ideas, especially in lighting design industry, emphasizes N. Bystryantseva in her conference speech. Art & Science demonstrates different ways of integration of XXI century latest research in robotics, information technology, biomedicine and optics into art and at the same time critically examines its role and use in society.

One of the results of this critical rethinking was development of biomedia expressive technology. K. Neidlinger, a designer and physiotherapist, introduced this technology and demonstrated the results. Biomedia is a synthesis of expressive technologies and lighting design, the technology, which involves biological feedback in relation to the user, and also acts as a means of communication and empathy increase. "This promotes what we call externalized intimacy, showing how one feels on the inside to the outside world," says Neidlinger [2, p. 32]. Biomedia technology is represented in several projects of smart clothes, made of fibreglass or multicolour LED elements, linked with sensors, which detect human feelings and emotions through changes in heart rate, respiratory rate, and activity of different parts of the brain. Due to such "smart clothes" signals, sent by a man into the environment, are visualized in colour and light. In the report, K. Neidlinger drew special attention to the opportunities bio media technology provides in different areas related to emotion expression: creation of new communication channels with autistics, artificial intelligence learned to recognize different emotional states, improvement of people's understanding of their own feelings and reactions.

How do new technologies facilitate interaction of different user groups with the outside world? Is the world ready to accept such openness? What can it offer in return for this openness? Will the inner world of a person be even more vulnerable due to blurring of boundaries between private and public? V. Petresin touched these issues in her conference speech and showed synergy of art, science and technology in art projects. Based on hypersurface theory she analyzes both physical barriers and those between the inner world of a man and society that exist only in our minds, integrating this research process with the artistic reflection of space, time, body, movement and emotion. Using the interaction of sound, image and light, Petresin visualizes transformation processes of the form and inside the form itself influenced by information. "My responsive multimedia pieces examine the synergy between technology, culture and society, as well as the dreams and pitfalls arising from their intersections." [3, p. 33].

Studying the influence of light on human mind, emotions, and behaviour, A. Spiridonova analyzes earlier examples of using light as a powerful and expressive influential tool. In the key work of Russian futurism, "Victory over the Sun" opera (1913), the lighting script is the central element of the innovative performance and highlights the performance against the theatre practices of that time. The artistic design of the play was made by K. Malevich, whose novelty and originality of methods, according to the memoirs of contemporaries, "was primarily in the use of light as a starting point that creates a form and legitimizes existence of things in space" [4, p. 229]. A. Spiridonova emphasizes, that the artistic experiments of the futurists with light provide valuable material for cultural studies of modern lighting performances.

Another point of view is presented by D. Fridman, a founder of Lux Aeterna Theater, who believes that a stressed person in metropolis needs some "intimate space" provided by the sanitary theatre, where 1 minute of your stay equals to at least 10–20 minutes of usual relaxation [5].

Taras Mashtalir devoted his presentation to availability of new forms of art and design to improve the environment of public spaces. Sonic sculpture is a multimedia work, "brought to life" at contact with a person and interacting with a person and the surrounding environment with the help of light and sounds. Sonic sculpture was presented at a small exhibition of light installations, held at the conference venue.

Art and science interaction was presented at the contests “Light: motivation or manipulation”, for the best light installation, and “Light & Movies”, for the best short video about light, which were traditionally held in the conference framework. The best light installation was the “Memory fragility” by O. Solyadkina, showing that thin threads of memories are the only link of the present with the past. The leading short film was “Light is inside every one of us” (B. Zhuk), devoted to reflections on the human dimension of light.

Special attention in the Art & Science framework was devoted to problems and challenges in architectural lighting and creation of qualitative lighting environment for storage, research and perception of works of art (E. Artemeva, O. Kruglov, J. Antipova). M. Frascarolo shared unique experience in special lighting design for the Sistine Chapel. The research lasted about three years and included many steps, among which was the colorimetric examination, definition of reference lighting spectrum for precise LED adjustment and modelling. Due to regulation of four colour channels with LED fittings (red, green, blue and warm white), the Chapel visitors can see the frescos as painted 500 years ago by great Michelangelo. A. Schulz highlighted the role of LED technology in lighting to create optimum storage conditions, perception of exhibits and formation of special museum “aura” [6].

Reflecting on transformation of the intangible into tangible with light, E. Prozorova reveals various aspects of interaction between material, technology, philosophy and art, which results in “emotionally experienced space” [7, p. 11]. N. Serov, meanwhile, tests harmony with algebra, and analyzes light as a “tool for generating ideas at information models level.” “Adequate understanding of complex systems requires information models (IM), where information has universal dimensions for all objects of nature and/or culture without exceptions”, which is the basic axiom of chromatism theory and methodology [8, p. 53]. This methodology enables correlation of “natural light information with the information of a new culture\civilization”: “the ontologically relevant information model of light may be built based on both material analysis of light (Faraday → Maxwell → Bohr-Schrödinger) and the ideal one (Plato → Goethe → Serov)” [ibid].

3. URBAN LIGHTING ENVIRONMENT

Spatial organization of any artificially created environment always reflects relevant to the era ideas about the spatiotemporal structure of the world. Modern reality (including social one) is ambiguous, fluctuating and unstable, it has a lot of moving points, and time flows differently in several dimensions (individual, sub-cultural, national and ethnic, etc.). These features are revealed in different levels of life: in the formation of object environment of modern cities, in personal and interpersonal relationships despite national and cultural differences [7]. Heterogeneous, ambiguous reality in the state of permanent transformation is that “model, which consciously or unconsciously (intuitively) is translated into modern public spaces, and lighting design takes leading part in this process [8,9]. Urban lighting environment at night is a reality created by a man in the era, when media, as “an essential element of modern urbanism, which is seen as a solution to urban crisis, actively undermine traditional modes of space and time” [10, p. 14]. How does reality fit human environment and whether it meets the society needs in terms of social, cultural, urban, information environment formation? How lighting environment affects social processes and people’s way of life? These and other questions were considered by conference participants in the context of city lighting.

Developing the issue “man – society – lighting environment” in a practical way, J. Vuorinen familiarized the audience with the projects of cyber-physical space created with lighting design, digital content design and light art. Due to a creative understanding of the possibilities of illumination light becomes “an enabler of ambient communication, participatory art and interaction”, effective way to “social cohesion” and information “unloading” in new communicative environment [11, p. 14]. Application of bio mimicry, sensor and computer vision, and printed electronics can create a “smart environment”, which “reacts” to different situations, individual preferences and people’s emotions and thus, cyber-physical space can be considered as analogous to living systems, actively interacting with a person.

Nocturnal urbanism is another promising area within the authentic approach framework, applied in cities with high level of light culture around the world. Principles, methodology, and convincing examples of nocturnal urbanity were presented by R. Narboni. Nocturnal urbanity is an alternative to illumination, which has been practiced since the mid-twentieth century "in response to the continued growth of vehicles in the city" [12, p. 16]. Nocturnal studies, considering urban nocturnal lifestyle, culture, traditions and residential needs is a fundamentally different strategy in lighting environment formation, which is people-and-future-oriented to morphological changes of public space.

The issue of humanization of urban spaces with lighting was raised by a number of speakers. Two recently practiced approaches, functional lighting and architectural lighting, are not able to create a uniform lighting environment, which forms unique urban image. "These two approaches skip one very important detail –lighting for people. Lighting, designed in accordance with the identified needs of a city, is able to reveal hidden layers of urban fabric, improve design quality, highlight cultural features and strengthen social ties", said Masorin [13, p. 26]. Introduction of lighting master plan has already proved to be efficient in solving this problem, as it enables simultaneous detailed study of all urban lighting projects.

Integrated consideration of the factors, influencing urban development and its lighting environment as a holistic phenomenon, brought together a variety of topics and round table issues: "It is necessary to formalize social goals of lighting design, as multidimensional social and predictive modelling is a complex and vital task for a city, which is solved in lighting only on the verbal level" (from the speech of V. Vasilyev); "Green spaces should be illuminated not only with functional or utilitarian lighting and holiday lighting for some events, but with well-installed architectural lighting" [14, p. 23]; " the process of choosing artistic strategy while designing of lighting scenes is very important. Lighting installations has wide potential and should take into account both the properties of the space and perception specific." [15, p. 17]; "visual arts ideas and unconventional approach to urban lighting can destroy the perception patterns of the subject-spatial environment, not only reflecting the language of contemporary visual culture and copying its plastic, but creating modern and evolving urban lighting design and its components" [16, p. 22].

Another important issue, actively discussed at the conference, was the impact of anthropogenic factor on human life.

4. TECHNICAL CULTURE AND NEW TECHNOLOGIES

One of the most acute problems affecting urban life quality is visual chaos created by light advertising. Besides negative impact on urban environment aesthetics and uncontrolled information load on people, excessive amount of light advertising poses a real threat to human health and life, as it creates emphasis, distracting drivers.

Research methods for studying speed of driver's reaction at different initial conditions with eye-tracking technology proved to be effective to solve this challenging and urgent task. Today there are various methods of studying distractions and their impact on people, however, they are not effective enough in complex analysis of large amounts of visual information, say S. Kolgushkina, V. Zhitlov. Eye-tracking technology, which is used for research in psychology and for study of website effectiveness, allows you to " to test the speed of driver's reactions on external stimuli", and "determine the real level of interest and focus lock" [17, p. 28].

Security issues in urban environment were discussed in S. Mitelev's speech, who convincingly argued the need for introduction of new approach to lighting of potentially dangerous areas. He stressed, that when designing lighting environment of pedestrian crossings, special attention should be given to lighting of a pedestrian, crossing the road, and not the pedestrian crossings.

Technologies, that are rapidly changing modern urban landscape, not just solve many pressing issues, but also pose new challenges for the professionals. For example, LED lighting in architectural lighting creates, in some cases, significant difficulties due to over-saturation, " when you use LEDs equipment in the synthesis of new materials in buildings" [18, p. 25]. Thus, different ways "to reduce LEDs emission using a detailed study of facade materials and design of fixtures" are considered [ibid].

Another aspect of illuminated object material and light interaction is revealed in applying coloured light and colour dynamics. At this stage, this type of lighting is used to create or change the colour shade of the illuminated surface and makes the analysis results of "interaction of light and form by using colour change in lighting" relevant [19, p.36].

5. EDUCATION

"No one except us will deal with the training of the youth. We must do what we are asked, otherwise we would never be asked", this phrase was said by R. Narboni at the round table devoted to the problems of education in the field of lighting design, and has become a kind of leitmotif of this discussion section of the conference.

Modern teenagers and students are the so-called generation Z, representatives of new communicative culture, which is formed under conditions of total informatization of society. They possess the specifics of perception and information processing, which require fundamentally new educational strategies, communication technologies and methods of knowledge transfer. Speakers and participants of the round table, devoted to the problems of modern education in the field of lighting design, are constantly facing this problem. Their exchange of experience in the field of design, implementation and efficiency of new experimental teaching methods was the main part of the round table discussion.

"Two major tasks of modern educational process, which is result-oriented and meets the needs of time, are to create a new approach to understand the world and the definition of the interdisciplinary connections. …Numerous factors analysis skill, ability to form internal relationships and choose an informed decision becomes necessary. It is important not just to see the world but also have design (contextual) thinking" is the vector of the modern educational process by N. Bystryantzeva [20, p. 43]. According to I. Ritter, modern lighting design is based on findings and results of scientific research, so it is a discipline to be studied and taught, and bachelor's and master's degree in lighting design should be recognized in future as the "educational launch" into professional life.

Developing Art & Science theme in the educational framework, V. Karpenko reveals the logic of shape-forming possibilities of light based on philosophical and psychological ideas and optical art: "the design goal of light composition is expressed in diversity, variability and contextually of application of its principles, and tools when creating new techniques of urban lighting, urban ensembles and dominants, buildings and structures, light forms and light plastics" [21, p. 49].

6. RESULTS

The International Research-to-Practice Conference "Lighting design-2016" revealed "space-time" perspective of major trends in the "man – lighting environment" system. Part of the raised issues during discussions gained perspective on its decision, however, new questions specified at discussions have to be answered in future.

Among wide range of discussed issues and reports at the conference a shift to humanistic component of lighting design and environmental issues in general is particularly noteworthy. This confirms that lighting design these days is a field where humanism is crucial in the world technological transformation process.

7. DISCUSSION SUMMARY

1. New ways of human interaction with space, information and other people in the formation of a new paradigm of communicative culture is one of the key tasks in different areas and professional fields related to the environment (social, urban, lighting, etc.).

2. Education and training of a new type of experts, i.e. next generation of lighting designers, ready to work with complex problems of the modern world in its various contexts, is possible only with introduction of innovative educational strategies with problem-based approach, interdisciplinarity, integration of scientific and creative methods.

3. The search for new methods and algorithms for data arrays processing to improve quality of lighting environment is the challenge for practitioners.

4. Competitive capacity in modern "light" market is ensured not so much by technology, but ideas and holistic predictive vision. This idea changes views on lighting design prospects.

Analysis of the discussed issues, prospective and current trends in lighting design determined the theme for the conference "Lighting design – 2017": "Identity through lighting environment".

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EFFICIENCY IN THE CHOICE OF POWER SERVICE CONTRACT AS WAY OF FINANCING POWER SERVICE ACTIVITIES

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ABSTRACT

The basic principles of energy service contracts for the external illumination sector are considered. An assessment of conditions of contract profitability for both parties is given.

Keywords: energy service contract, energy service actions (measures)

Calculations show that potential beneficiaries of energy service contracts (ESC) are public sector customers who need to cut costs due to their financial circumstances, for example as a result of state and municipal cuts.

1C From December 2009, Federal law #261- ФЗ "On energy saving and increasing energy efficiency, as well as on the introduction of amendments into separate enactments of the Russian Federation" came into force, according to which Federal law #94- ФЗ "On placing orders for the supply of goods, works and services for state and municipal needs" was added with a new separate section regulating the order of placing budgetary commissions for energy services.

The purpose of energy service contracts is to create conditions for energy saving and to improve the efficiency of energy resource use, including electricity.

To achieve this, the contractor shall finance energy service measures. Subsequently the customer compensates the contractor from the savings made as a result of decreased energy consumption. Therefore, establishing an ESC allows introducing energy saving measures without spending budgetary funds directly when introducing energy services. Budgetary allocation for power consumption is recorded at the end point of the ESC for the period necessary to compensate the costs to the contractor from the efficiency savings.

After repaying the contractor, the budgetary costs continue to reduce directly as a result of the introduction of the energy saving measures.

The ESC beneficiary as the state (municipal) customer is the party responsible for procuring energy resources, and the contractor is the party who implements and finances the energy service measures at their own cost and expense.

According to P. 3. of Article 72 of the Budgetary code of the Russian Federation, an ESC can be let for any period, without being limited by a validity period of the approved limits of budgetary obligations.

The question arises; what can an ESC achieve in the sphere of external illumination sphere? There are several opportunities: introduction of measures which lead to energy savings; direct replacement of in situ light devices and sources with more energy efficient models; measures, which enable usage schemes of partial switching off at night; installation of individual or group illumination adjustment systems etc..

It follows from the general characteristics of the ESC that its benefit is the risk transfer of an inefficient solution to the investor and the fact that no direct budgetary financing for efficiency is needed at the introduction stage.

At the same time, if we presume that state (municipal) authorities are able to estimate efficiency of the applied energy saving technologies and to determine independently what energy saving measures lead to resource savings, then the only benefit of the ESC is the specific character of its financing. And here it is important to understand exactly how beneficial an ESC can be for the budget.

In the event of accomplishing current budgetary costs, and if energy saving measures are financed directly from the budget, an ESC will be not profitable for the budget because the investor must discount the profit and the investment or availability of credit by the energy service measure cost.

WORKED EXAMPLE

Let's consider one of the simplest cases of the energy service measures for energy saving in external illumination: the replacement of light device A with an 125 W arc lamp with a more efficient light device B with an 70 W HPSL.

As it can be seen from the Table, the annual electric power saving as a result of this is equal **to 1134 roubles** (2520 rub – 1386 rub) per device.

Let's calculate the investor's expenses without accounting for incremental costs i.e. the costs of the light device itself within an average price interval. For example, the Orion ЖКУ20–70–001 luminaire (with glass and ballast *IP44* protection degree) produced by GALAD SPA has a wholesale price of 3730 rub with VAT.

With a profitability rate of 20 % or 746 rub, the cost of the luminaire is 4476 rub (3730 rub + 746 rub).

Thus with direct financing, the state (municipal) customer could commission the introduction of the new equipment at a cost of 4476 rub for this energy saving measure, and the investor would regain the cost with a the profit of 746 rub.

When financing the project at the investor's expense and compensating the investor's costs by means of monetary trenches using sums equal to the electric power saving, the investor would recalculate the project cost with income discounting.

There is a need to evaluate costs over time as the cost of monetary resources changes with time. In other words, the goods which we can buy for 100 roubles today will cost 110 roubles in a year's time, in two years – 120 roubles, and so on, i.e. purchasing cost of money decreased under inflation conditions.

Under ESC conditions, compensation to the investor is made through annual payments equal to the money saved for electric energy (an annual payment in our example is equal to 1134 roubles), these cash flows should be reduced to the current cost.

Hence, we will carry out the following calculations. Investments of the investor in our example are equal to 4476 roubles (this is the cost of the luminaire with a profitability rate of 20 %, which satisfies the investor). Compensation of the investments is made by means of annual payments of 1134 roubles (the cost of the saved electric energy). For discounting, we need to determine a barrier rate or discount rate. Economics tells us that this value should be equal to a minimum permissible income rate since the investor could invest available funds into some other project, or place them to a bank deposit etc.. The most effective method of determining the discount rate is according to Fischer's [1] formula, which considers both profitability with and inflation losses. If inflation rate I is equal to 6 % per annum according to a moderately positive forecast, and an acceptable profitability level R is equal to the bank deposit rate of 7 % per annum, then the discount rate E using Fischer's formula

$$E = (1+I/100) \times (1+R/100) - 1$$ is equal to
$$(1+ 0.06) \cdot (1+ 0.07) - 1 = 0.1342$$ (i.e. 13.42 %).

Now we will recalculate cash flows into the current costs:

The first year: 1134/1.1342 = 999.82 rub.

The second year: 1134/(1.1342·1.1342) = 881.52 rub.

The third year: 1134/(1.1342·1.1342×1.1342) =777.22 rub.

The fourth year: 1134/(1.1342·1.1342×1.1342·1.1342) = 685.26 rub.

The fifth year: 1134/(1.1342·1.1342×1.1342·1.1342·1.1342) = 604.18 rub.

The sixth year: 1134 / (1.1342·1.1342·1.1342×1.1342·1.1342·1.1342) =532.68 rub.

The sum of the discounted cash flows for six years is equal to 4480.68 rub (999.82 + 881.52 + 777.22 + 685.26 + 604.18 + 532.68).

The difference between actual investments and discounted total cash flows is a factor of net present value *NPV*. *NPV* is calculated using predicted cash

Table. An example of an evaluation of energy service measure cost efficiency

Light device	Lamp power, W	Loss factor in the ballast	Annual power consumption at an average 4000/year lighting hours, kW·h	Cost of annual power consumption at an electricity price of 4.5 rub/kW·h, roubles.
A	125	1.12	125·4000·1,12/1000 = **560**	560·4,5 = **2520**
B	70	1.1	70·4000·1,1/1000 = **308**	308·4,5 = **1386**

flows connected with the planned investments according to formula [2]

$$NPV = \sum_{i=1}^{N} \frac{NCF_i}{(1+r)^i} - Inv,$$

where NCF_i is net cash flow for period i; *Inv* is initial investments; r is the discount rate (cost of the capital needed for the investment project). In case of a positive *NPV*, the capital investment is considered effective. In our example *NPV* = 4480.68 rub – 4476 rub = 4.68 rub.

Accordingly, the investor reaches a positive *NPV* in six years with an ESC cost of 6804 rub (1134 rub × 6 years).

As a consequence, from the point of view of budgetary expenditure evaluation, financing energy service measures by means of an ESC, is 52 % more expensive for the budget than direct financing (6804 rub / 4476 rub = 1.52).

Discounting is even more complex if an investor uses borrowed funds (credit resources) for financing energy service measures. The investor as a borrower in this case has an opportunity to repay debt with money of a reduced purchasing power and will only discount their own profit. However, when crediting an investor according to the bank rate, which exceeds their own barrier rate, the project repayment period for the investor increases, and consequently the ESC cost to the budget will also increase.

According to the above analysis, before financing energy saving measures through an ESC, a public sector customer should calculate and compare the financial flows of their expenditure.

In our opinion, it is more advantageous for a budgetary customer to achieve energy savings by placing a traditional state order for services, except for in cases when energy service measure cost corresponds to no more than 1–2-year energy saving obtained as a result of the introduction of energy service measures.

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METHODS OF CALCULATION OF FLOODLIGHTING UTILISATION FACTOR AT THE DESIGN STAGE

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ABSTRACT

The main aim of this work is to present different methods of calculation of these new parameters: floodlighting utilisation factor, useful luminous flux, loss of luminous flux and coefficient of floodlighting utilization factor. Each method is carefully described. There is also a general analysis of the assumptions and restrictions used in the calculations. The results of the calculations are presented and broadly discussed with reference to a very simple and a more complex floodlighting design. It was found that these parameters are very helpful and convenient in the assessment of the quality of floodlighting at the design level.

Keywords: floodlighting, energy efficiency, light pollution, floodlighting utilisation factor

1. INTRODUCTION

When we look from the perspective of time, we could say that the day when humans invented fire and used it to light up the dark night, was one of the most significant days in our history. The time for work became longer because of this invention. It has also had an impact on the evolution of technology through the ages. Artificial sources of light were developed in parallel to the development of technologies whose main aim was to make work much easier and more effective. The development proceeded from fire to torch, to oil lamp and finally, at the end of 19th century, to electrical light sources. The incandescent lamp, the discharge lamp and the LED are evidence of this technological growth. They are also a sign that our need to search for and find more refined solutions is infinite. However, the last few years have shown that universal access to this technology and the frequent usage of modern lighting equipment (generally LED lamps [1]), as well as the very low cost of manufacturing, has caused many different problems and threats, which form the opportunities of research for a large number of scientists.

1.1. The issue of energy efficiency

20th century was definitely the most effective period in the development of light sources. The usage of electrical energy became much more common due to the fact that people began to illuminate more frequently. The need to pay attention to the issue of the energy efficiency of lighting began to be realised, both in developed and in developing countries [2,3]. The matter of saving electrical energy has become a problem, which is now widely commented on in terms of its effect on the future of our planet [4]. Many experts consider 20th century as the "Century of Energy Efficiency". The latest research shows that there is a great energy-saving potential in lighting [5]. Nowadays, standards and legal regulations, aimed at the reduction in use of electricity for lighting purposes, have been created [6]. A new and interesting issue is that of Nearly Zero Energy Buildings (nZEB). This is also the basis of many engineering analyses [7,8,9].

1.2. The issue of glare

The phenomenon of glare is one of the main concerns in the area of lighting technology [10]. It is very important not only for interior lighting but also for exteriors. In the case of road and road lighting, there are some consequences related to traffic safety regulations. The analysis of this phenomenon is based on a theoretical calculation [11,12], or luminance measurement, which is quite problematic, even allowing for the contemporary possibility of using imaging luminance measuring devices (ILMD) [13].

1.3. The issue of light pollution

Light pollution is quite a recent problem. It is connected with many negative occurrences, such as skyglow, light trespass, and the lack of proper visibility of the stars [14, 15]. The requirements and regulations are not definite in this area. There are some guidelines [16, 17]; however, only a few countries e.g. Taiwan [18], have legal regulations associated with the reduction of light pollution. Scientists are also trying to measure light pollution and floodlighting utilisation factor in a quantitative way [19,20,21]. Calculation models of skyglow are created as well [22]. There are some attempts at analyses in order to improve the usage of luminous flux emitted from luminaires, which can lead to energy saving and a decrease in light pollution [23,24].

1.4. The photobiological threat issue

The development of light sources creates the need for the analysis of the influence of type of lighting and lighting parameters on plants and living organisms [25,26]. "Bad lighting" or, more specifically, spectral power distribution (especially at high energy in the range of wavelength (420–560) nm) can have a great impact on circadian rhythms, not only in humans, but also in animals and plants.

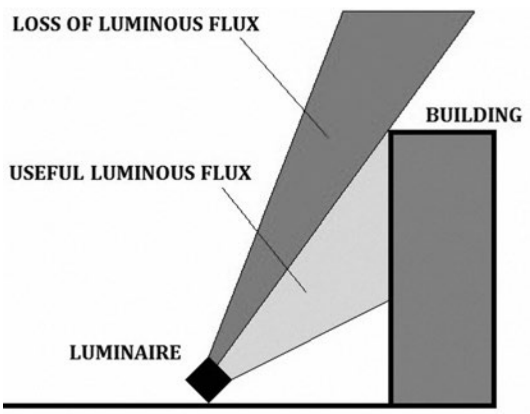

Fig. 1. The schematic approach to luminous flux analysis in floodlighting

We need to search for methods that allow us to design lighting in a very considered way, in order to counteract the above problems and threats. These methods should allow us to eliminate potential threats or to let us have conscious control over them.

2. NEW PARAMETERS AND CALCULATION METHODS

At present, there are no requirements or regulations in the literature connected with floodlighting design. However, there are some general recommendations [27, 28] and publications, which have been prepared by specialists with good practice in this field [29]. The problems of energy efficiency and light pollution have not been presented yet in the context of floodlighting. Contemporary assessment is done only at an aesthetic level and is rather subjective. However, there is the possibility of using some parameters, whose main aim is to assess floodlighting designs at the technical and engineering level. These parameters are shown by the formulae (1–7). The precise definitions are described in the literature [20,24].

$$FUF = \frac{\varphi_u}{\varphi_t} \cdot 100\ [\%], \tag{1}$$

$$\varphi_t = \sum_{i=1}^{n} \varphi_{0_i}\ [lm], \tag{2}$$

$$FUF_{\max} = \frac{\varphi_t}{\varphi_{tlum}} \cdot 100\ [\%], \tag{3}$$

$$\varphi_{tlum} = \sum_{i=1}^{n} \varphi_{lum_i}\ [lm], \tag{4}$$

$$\varphi_{loss} = \sum_{i=1}^{n} LOR_i \cdot \varphi_{0_i} - \varphi_u\ [lm], \tag{5}$$

$$\varphi'_{loss} = \frac{\varphi_{loss}}{\sum_{i=1}^{n} LOR_i \cdot \varphi_{0_i}} \cdot 100\ [\%], \tag{6}$$

$$CFUF = \frac{FUF}{FUF_{\max}} \cdot 100[\%], \quad (7)$$

where:

FUF is the floodlighting utilisation factor,

LOR is the luminaire output ratio,

$FUF_{\max}$ is the maximum value of floodlighting utilisation factor,

φ_u is the useful luminous flux,

φ_{loss} is the loss of luminous flux,

φ'_{loss} is the relative loss of luminous flux,

φ_t is the total luminous flux (of all light sources),

φ_0 is the rated luminous flux (of a light source),

φ_{tlum} is the total luminous flux (of all luminaires),

φ_{lum} is the rated luminous flux (of a luminaire),

$CFUF$ is the coefficient of floodlighting utilisation factor.

These formulae allow the calculation of the floodlighting utilisation factor, useful luminous flux, loss of luminous flux and coefficient of floodlighting utilisation factor. It has to be remembered that floodlighting has, until recently, focused only on visual effects and on ensuring lighting consistency and other aesthetic features. This fact confirms the need to determine what proportion of luminous flux emitted from the light sources used in the floodlighting project is actually being aimed at the designated surfaces. The Floodlighting Utilisation Factor (FUF) can be a useful parameter to enable this to be done [20]. It is defined as a ratio of useful luminous flux, which is aimed at the surface of a floodlit object and which causes a specific visual effect (such as luminance), to the total luminous flux, coming from all the light sources used in that lighting solution. By contrast, the part of the luminous flux, which is not aimed at the object, can be called the loss of luminous flux [20], Fig.1. It is exactly this part of the luminous flux, scattered around the floodlit object, which causes light pollution (provided that the luminaires are directed to the upper hemisphere) [20].

The definitions of these parameters are not new but the application is definitely innovative (in the floodlighting area). These calculations can be obtained by using Autodesk 3dS Max [30]. This software was chosen because of its usefulness during the process of floodlighting design by the method of computer visualisation [31] and because of the precision of the calculations [32]. The values of illuminance (illuminance distribution) can be obtained by using the calculation plane Light Meter. The user has the opportunity of changing the accuracy of the calculation by modifying the amount of calculation points. The Light Meter can be of any arbitrary size and the user can bend it freely or set it in any position. This allows for the possibility of creating a number of different calculation types. The basis of these methods is the illuminance distribution or luminance distribution on each plane. When the area S of this plane is known, the luminous flux φ, which reaches the plane, can be calculated by (8).

$$\varphi = \int_S E ds[lm]. \quad (8)$$

Useful luminous flux or loss of luminous flux can be calculated, depending on how the planes are positioned with respect to the illuminated object. Therefore, the calculation methods can be divided into methods for the calculation of useful luminous flux and methods for the calculation of loss of luminous flux. Each of these methods has some special variants, and some advantages and disadvantages. Whichever method is chosen, all these parameters (1–7) can be calculated.

3. METHODS FOR THE CALCULATION OF USEFUL LUMINOUS FLUX

3.1. The method of evaluation of luminance by eye

This is the only method where using the Light Meter is not necessary. It is based on the assessment by eye of the average luminance on the pseudo colours diagram, Fig. 2. a, generated by the 3dS MAX. When the average luminance and area are

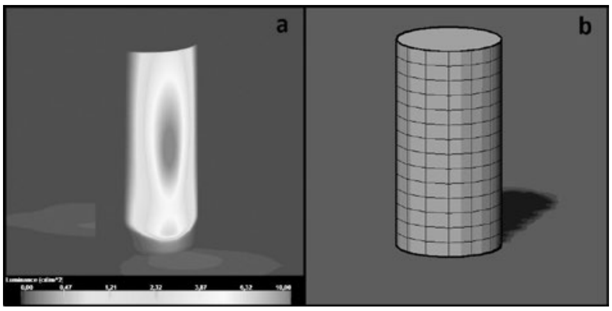

Fig. 2. Methods for the calculation of useful luminous flux: a – the method of evaluation of luminance by eye (luminance distribution on surface in pseudocolors scale), b – calculation grid on the surface of the object (object-surface method)

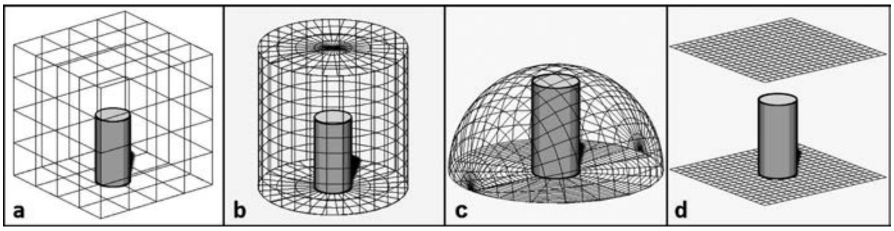

Fig. 3. Schemes of methods for the calculation of the loss of luminous flux: a – the cuboid method, b – the cylinder method, c – the hemisphere method, d – the parallel planes method

known, the useful luminous flux can be calculated by (9).

$$\varphi_u = \frac{\pi L_{avg} S}{\rho} [lm], \quad (9)$$

where:
L_{avg} is an average value of luminance,
S is an area,
ρ is the reflectance factor.

This method is very quick to use. However, it has a very low accuracy. The values of average luminance are subjectively evaluated. Moreover, there is a problem connected with the proper value of the reflectance factor. Even small changes in it can cause a large discrepancy in the results. Therefore, this method will not be discussed any longer. In order to increase the accuracy and reliability of the results, methods based on the distribution of illuminance on the plane Light Meter should be used.

3.2. The object-surface method

This method is based on the positioning of the Light Meter on the surface of the illuminated object, Fig. 2b. By obtaining the illuminance distribution on the illuminated object and when the main dimensions of the surface are known, the useful luminous flux can be calculated by (10). This method is easier to use for an object with quite simply geometry, because of the difficulty in manipulating the Light Meter.

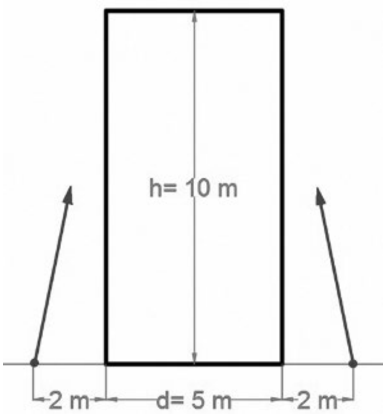

Fig. 4. The main dimensions and method of illumination of the cylinder

$$\varphi_u = ES = Eab \ [lm], \quad (10)$$

where:
E is an average value of illuminance, a and b are the main dimensions of the surface.

4. METHODS FOR THE CALCULATION OF LOSS OF LUMINOUS FLUX

The methods for the calculation of loss of luminous flux are very helpful, especially when the geometry of the illuminated object is more complex and there is no possibility of positioning the Light Meter on the surface of the object.

4.1. The cuboid method

The cuboid method is based on the enclosure of an illuminated building by six Light Meters, forming a cuboid (or a cube, depending on the geometry of the inside object), Fig. 3a. By summing the luminous flux from every wall of the cuboid, we can obtain the loss of luminous flux (11).

4.2. The cylinder and hemisphere methods

In a similar way to the previous method, the loss of luminous flux can be obtained when the illuminated object is inserted into Light Meters that are bent into the form of a cylinder or hemisphere, Fig. 3. b, c. The value of loss of luminous flux can be obtained based simply on the geometrical formulae, which represent the area of a cylinder or hemisphere with a circular-shaped base (12–13).

Fig. 5. Computer visualisation of the concept of floodlighting of the Rector's Palace of WUT

Fig. 6. Luminance distribution of the concept of floodlighting of the Rector's Palace of WUT

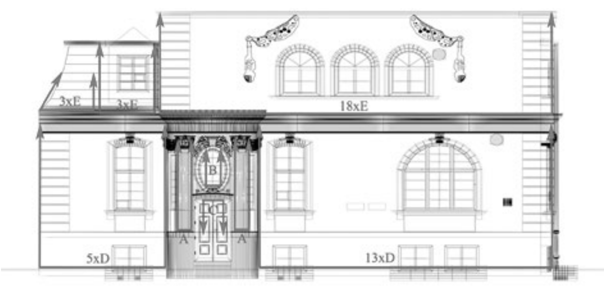

Fig. 7. Scheme of location and angle of direction of the lighting equipment (south wall)

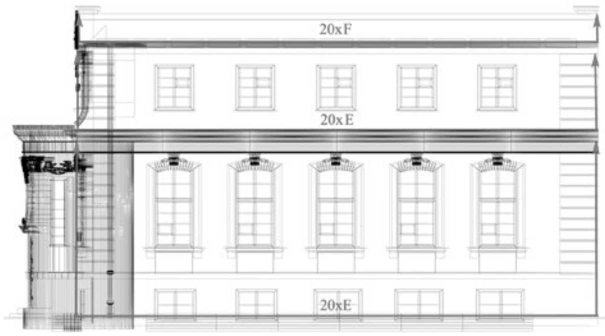

Fig. 8. Scheme of location and angle of direction of the lighting equipment (east wall)

For a cube:

$$\varphi_{nu} = \sum_{i=1}^{6}(E_i S) = \sum_{i=1}^{6}(E_i ab)\ [lm], \qquad (11)$$

For a cylinder:

$$\varphi_{nu} = \pi R\left[R(E_{b1} + E_{b2}) + 2HE_s\right]\ [lm], \qquad (12)$$

For a hemisphere:

$$\varphi_{nu} = \pi R^2 (E_b + 2E_{Sp})\ [lm], \qquad (13)$$

where:

E_i is an average illuminance on the particular wall of a cube,

E_{b1}, E_{b2}, E_b are the average illuminance at the base of a cylinder or hemisphere,

E_{Sp}, E_s are the average illuminance on a hemisphere or on the side surface of a cylinder,

a and b are the main dimensions of the calculation of a surface,

R is the radius of a hemisphere or cylinder,

H is the the height of the cylinder.

4.3. The parallel planes method

The last method of calculation is the parallel planes method. The manner of insertion of the Light Meter onto the illuminated object is presented in Fig. 3d. There are two planes in this method: the first of them is located above the illuminated object and the second below the object. The calculation formula is the same as in the case of the object-surface method, but now the formula (10) allows us to calculate the value of the loss of luminous flux (14).

$$\varphi_{nu} = (E_A + E_B)ab\ [lm],\ \text{where} \qquad (14)$$

E_A is an average illuminance on the plane which is located above the object,

E_B is an average illuminance on the plane which is located below the object.

5. CALCULATION FOR A SIMPLE DESIGN OF FLOODLIGHTING

All of the above calculation methods were tested on a simple design of floodlighting. This model

Table 1. Technical data of lighting equipment for a simple floodlighting design

Light source	Amount	ϕ_0, lm	P, W	LOR, %	φ_{lum}, lm	$\delta_{1/2}$
MH	2	3300	35	67	2211	C0–180: 16 C90–270: 16

Table 2. Results of the calculation for a simple floodlighting design

Method	Type	E, lx	S, m^2	φ_{loss}, lm	φ_u, lm	FUF, %	CFUF, %
Object surface	object	10,37	157	2794	1628	25	37
The cube 20m × 20m	top	5,25	400	2100	1440	22	33
	bottom	0,01	400	4			
	front	0,71	400	284			
	back	0,71	400	284			
	left	0,39	400	156			
	right	0,40	400	160			
				2984			
The cylinder R=10m H=20m	top	9,53	314	2991	451	7	10
	bottom	0,00	314	0			
	left side	0,78	628	490			
	right side	0,78	628	490			
				3971			
The hemisphere R=11,3m	base	0,00	314	0	2329	35	52
	hemisphere	2,61	802	2093			
				2093			
The parallel planes 100m x 100m	above	0,30	10000	3000	1422	22	32
	below	0,00	10000	0			
				3000			

consisted of an object with very simple "the cylinder" geometry with a height of 10 m and a radius of 2,5 m, Fig. 4. The cylinder was illuminated with two ground-recessed luminaires. The spatial luminous intensity distribution of these luminaires (for metal halide sources) was rationally symmetrical and the power of each of them was 35 W. The basic lighting and electrical parameters are presented in Table 1. The calculations were carried out only in relation to direct illuminance (the reflectance factor for all the materials in this model was zero, $\rho=0$). The computing grid maximum dimensions were 20 cm x 20 cm. The results are presented in Table 2.

6. CALCULATION FOR A COMPLEX DESIGN OF FLOODLIGHTING

Having shown the calculation for a simple model, it is now necessary to show a calculation for a complex design. The object, which formed the basis of this part of the research, was a floodlighting design, which has already been prepared for the Rector's Palace of the Warsaw University of Technology (WUT). The visualisation of floodlighting is presented in Fig. 5, and the luminance distribution of this concept in Fig. 6. The main concept of this floodlighting design is based on the usage of linear LED luminaires. All the facades are illumi-

Table 3. Summary of the lighting equipment for floodlighting of the Rector's Palace of WUT

Symbol	Light source	Number	ϕ_0, lm	P, W	*LOR*%	φ_{lum}, lm	$\delta_{1/2}$
A	LED	2	636	16	67	426	C0–180: 3 C90–270: 3
B	LED	1	636	16	63	401	C0–180: 13 C90–270: 7
C	LED	1	1260	50	39	491	C0–180: 10 C90–270: 27
D	LED	18	1584	50	39	618	C0–180: 10 C90–270: 27
E	LED	64	1584	43	39	618	C0–180: 9 C90–270: 26
F	LED	20	504	14	39	197	C0–180: 9 C90–270: 26

Table 4. Summary of useful information for both a simple and a complex floodlighting design

Type	Number	φ_{tlum}, lm	φ_t, lm	FUF_{max}, %
Simple design	2	2211	6600	67
Complex design	106	56360	143136	39

nated from bottom to top in such a way as to create a highly uniform effect. There are delicate lighting accents on the baroque-style entrance and on the decorations above it. The location, the directionality, and the technical data for the lighting equipment are presented in Figs. 7,8 and Table 3.

7. DISCUSSION AND CONCLUSION

The results show that each particular method is somewhat different from the other one – give different results. However, the main aim of this paper was only to introduce the possibility of the calculation of these new parameters at the design level. The analysis (e.g. of the influence of the size of the computing grid on each particular method) is not discussed in detail.

In the case of a simple floodlighting design, similar values of the floodlighting utilisation factor (22–25)% are obtained in the surface-object method, the cuboid method and in the parallel planes method. The cylinder method and the hemisphere method have divergent results, which could be caused by the need to manipulate the plane of the Light Meter in these two methods or by the low accuracy of the computing grid in this situation.

In the case of a complex floodlighting design, there is a much higher convergence in the results obtained. However, the closest values of the floodlighting utilisation factor (18–20 %) are obtained for the same methods as in the previous case. The results for the cuboid method and hemisphere method are much closer to the others in this case (21 % and 24 %). This seems to be connected with the use of much larger computing planes. In the case where the calculation with extremely high accuracy is required, it is necessary to be aware of the need for a compromise between the size of the computing plane and the density of the computing grid, depending on the parameters of the computer. However, it seems that the use of a sufficiently large computing area, with a highly accurate calculation grid, will unify the calculation results for all methods.

The calculations show that the values of these parameters are relatively small (FUF: (20–30)%; CFUF: < 62 %). There is also a high level of dependence between the floodlighting utilisation factor and the luminaire output ratio. It is necessary to use high quality lighting equipment in order to increase energy efficiency. It has to be ensured that the final result of the floodlighting design is as good as possible from a technical and engineering point of view and from an aesthetic angle. The analysis described

Table 5. Results of the calculation for a complex floodlighting design

Method	Type	*E, lx*	*S*, m^2	φ_{loss}, lm	φ_u, lm	FUF, [%]	CFUF, %
Object surface	part 1	199,32	13,2	27162	2631	20	51
	part 2	45,15	30,0		1355		
	part 3	106,48	69,5		7402		
	part 4	40,54	39,4		1599		
	part 5	58,72	70,8		4157		
	part 6	93,86	75,7		7103		
	part 7	47,97	103,2		4951		
					29198		
The cube 30m x 30m	top	18,93	900	17037	26233	18	46
	bottom	0,47	900	423			
	front	3,09	900	2777			
	back	2,05	900	1845			
	left	2,76	900	2484			
	right	6,18	900	556			
				30128			
The cylinder R=15m H=30m	top	13,61	695,6	9467	30373	21	54
	bottom	0,43	695,6	299			
	left side	7,82	1413	11050			
	right side	3,66	1413	5172			
				25987			
The hemisphere R=24 m	base	0,27	1963	530	33983	24	62
	hemisphere	6,04	3617	21847			
				22377			
The parallel planes 100m x 100m	above	0,04	10000	400	26560	19	49
	below	2,94	10000	29400			

in this work could make it easier to apply floodlighting design in the context of a rational use of energy in the form of useful luminous flux, as well as in the reduction of the adverse effects of environmental light pollution in floodlighting.

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CONTENTS

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