ISSN 0236-2945

LIGHT & ENGINEERING

Volume 27, Number 5, 2019

Editorial of Journal
“Light & Engineering” (Svetotekhnika), Moscow

The purpose and content of «Light & Engineering» is to develop the science of light within the framework of ray, photometric concepts and the application of results for a comfortable light environment, as well as for visual and non-visual light technologies, including medicine. The light engineering science is a field of science and technology and its subject is the development of methods for generation and spatial redistribution of optical radiation, as well as its conversion to other forms of energy and use for various purposes.

The scope of journal includes articles in the following areas:

- Sources of light;
- Light field theory;
- Photometry, colorimetry and radiometry of optical radiation;
- Visual and non-visual effects of radiation on humans;
- Control and regulation devices for light sources;
- Light devices, their design and production technology;
- Light devices for the efficient distribution and transportation of the light energy: hollow light guides, optical fibers;
- Lighting and irradiation installations;
- Light signaling and light communication;
- Light remote sensing;
- Mathematical modelling of light devices and installations;
- Energy savings in light installation;
- Innovative light design solutions;
- Photobiology, including problems of using light in medicine;
- Disinfection of premises, drinking water and smell elimination by UV radiation technology;
- Light transfer in the ocean, space and other mediums;
- Light and engineering marketing;
- Legal providing and regulation of energy effective lighting;
- Light conversion to other forms of energy;
- Standardization in field of lighting;
- Light in art and architecture design;
- Education in field of light and engineering.

Journal "Light & Engineering" had been founded by Prof. Julian B. Aizenberg in 1993

LIGHT & ENGINEERING

СВЕТОТЕХНИКА

Editorial of Journal "Light & Engineering/Svetotekhnika"

Moscow, 2019

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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 six issues, with about 80–120 pages per issue. Each paper is reviewed by recognized world experts.

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SENIOR LIVING – LIGHTING, CIRCADIAN RHYTHM AND DEMENTIA I[1]

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ABSTRACT

The Real Estate Fund of Pension and Disability Insurance (Nepremičninski Sklad) in Slovenia, founded in1997 is the owner of 3255 properties in 116 locations throughout the country and is intended for solving housing issues of pensioners of 65 years or older and other elderly persons who are allowed independently to live. The lease contracts are concluded for an indefinite period of time. The aim and vision of the Fund is to improve the quality of life for the elderly tenants by adapting the living environment, the flats and surroundings according to the physical needs of aging tenants.

Homes for seniors often have low light levels and poor light spectrum caused by fluorescent or incandescent lighting. Demographic changes in most European countries show rising average life expectancy which means that the number of people with weak visual capacity or visual impairment is increasing. Equally the risks of injuries due to poor lighting conditions are increasing, e.g. missing a step resulting in a hip joint fracture. Better lighting conditions are of critical importance for aging population, as stated also in the recently published CIE227:2017.

To facilitate safe environment for the elderly, the Fund in 2013 initiated a lighting research study that should provide facts and evidence for a lighting standard for their own premises.

[1] Editing and styling by Elena P. Emelyanova, senior lecture of Institute of Linguistics and International Communication at I.M. Sechenov First Moscow State Medical University

Keywords: elderly people, sleep problems, dementia, circadian rhythm, immune defence insomnia, blue light hazard

1. INTRODUCTION

For elderly people, one of the first signs of aging is the deterioration of visual capacity. Other signs are the weakening of muscular strength and mobility often followed by sleep problems.

This often deprives older people of healthy outdoor walks and exercise and exposure to daylight which further affects mood and wellbeing in a negative way. In addition, this also increases the risks for dementia for a growing number of older people. A disease which currently affects about 1.5 % of the population is estimated to increase to 3 % within 20 years, mainly among people older than 65 years. In Slovenia, there are around 335000 persons older than 65 years today and out of these about 5000 persons are affected by dementia. This is a heavy burden not only on the society but even more on relatives and other caregivers. Today this cost is calculated to be around 1 % of the GDP.

A lot of recent research find strong connections between disturbances of the circadian rhythm, immune defence insomnia, risks of increased development of cancers, diabetes and also dementia. It is also well known, that the circadian rhythm is depending on the ability to register the daily changes of the light and dark period via signals through the eyes.

The aging eye, which seriously limits the visual experience and perception of the environment is mitigating the ability to register those changes. The pupil decreases in size, the lens inside the eye becomes thicker and is less transparent for the healthy blue light and the lens scatters more light causing objects and colours to appear less vivid. Furthermore, older people begin to lose retinal neurons which not only compromises the ability to see but also to clearly register the change of light spectrum over the day which is essential to regulate the circadian rhythm or, the "body clock".

Homes for seniors often have low light levels and poor light spectrum caused by fluorescent or incandescent lighting. Demographic changes in most European countries show rising average life expectancy which means that the number of people with weak visual capacity or visual impairment is increasing. Equally the risks of injuries due to poor lighting conditions are increasing, e.g. missing a step resulting in a hip joint fracture. Better lighting conditions are of critical importance for aging population, as stated also in the recently published CIE227:2017.

To facilitate safe environment for the elderly, the Fund in 2013 initiated a lighting research study that should provide facts and evidence for a lighting standard for their own premises.

2. ASPECTS OF LIGHTS INFLUENCE ON THE HUMAN BODY

From the beginning of the study it was decided that all aspects of lights influence on the human body should be considered, not only the IF (visual aspects) but also the NIF (nonvisual aspects).

Going through a broad spectrum of research reports it was very early understood by the team that an important key for the wellbeing of the elderly was a steady circadian rhythm. To establish this, the research reports show that the melatonin secretion should be high during evenings and nights to give a good sleep but stopped completely in the mornings to enable the production of cortisol, serotonin and other hormones essential for an alert and active life.

A great number of reports also showed that the key to this was to maintain a steady and robust daily pattern of light and dark but also the right kind of light spectrum at specific times of the day. For instance, to stop the melatonin secretion when the day starts it is important that the light spectrum should contain enough amount of blue light within the action spectra for melanopsin (455–490) nm in the so called ipRGC ganglion cells, which transmit light signals to the pineal gland where the melatonin is created. Towards the evening it was important that the light is switching out the blue action spectrum so that the melatonin secretion could start again and put the body to rest and sleep.

During the research the team also found a lot of other important effects of the NIF light and the importance of a steady circadian rhythm.

Among elderly more than 50 % suffer from chronic sleep disturbances, and poor sleep can be linked to a variety of problems like increased cardiovascular problems, disruption of endocrine functions, decline of immune functions, stability problems and poor cognition.

Several studies have shown a connection of increased risk for development of dementia and a disturbed circadian rhythm. In the studies it has been pointed out that even people already affected by dementia feel better when having a light exposure stimulating the circadian rhythm.

Since the proper lighting to stimulate a natural circadian rhythm seems to be the best medicine to avoid a number of diseases – to get the biological clock in order and at the same time stop or slow down the development of dementia, the planning of the light must be taken very seriously.

Various research projects show evidence that it is most beneficial for the elderly to use considerably higher illuminance than the standard recommendations. Large illuminated surfaces, glare free lighting and no flicker also bring important benefits.

A conclusion of the studies, which was not only about the spectrum of the day and evening light but also very much about the other aspects of light like the light distribution, luminance and glare,

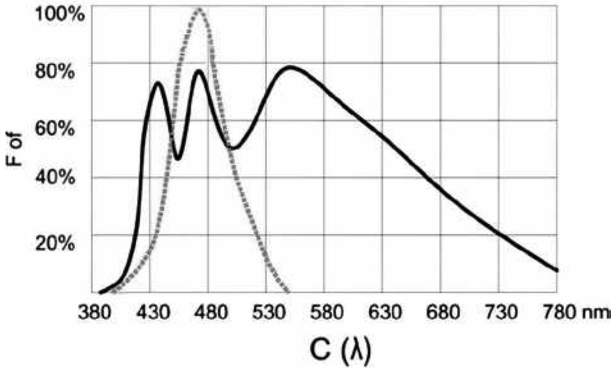

Fig.1. Peak of the day spectrum curve coincides with the peak of circadian curve (dashed)

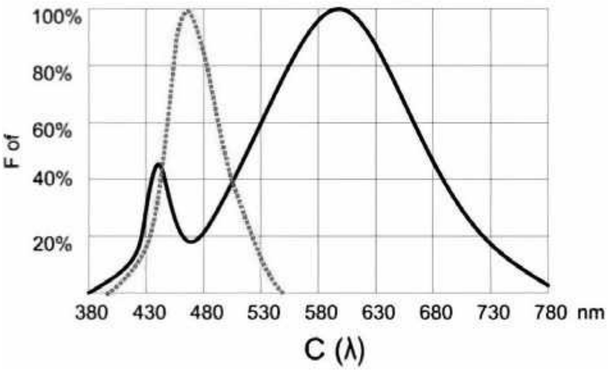

Fig.2. Night spectrum curve, however, has a valley where circadian curve (dashed) peaks

flicker and spatial reception resulted in a different kind of tender documentation which caused a lot of concerns and negative reactions among the bidders for execution. Especially the requirement of the sufficient amount of "blue light" within the action spectrum for melanopsin filtered out several of the bidding manufacturers. Only after repeating the tendering process several times did the Fund get appropriate offers at acceptable costs.

3. TECHNICAL REQUIREMENTS FOR LIGHTS AND SURFACE LIGHTING

The following is an example of the specifications of key requirements for the elderly lighting, as used in Izola pilot project:

3.1. General Information on the Tender Documents for the Scope of Lighting

Since the invention of the electrical light about 150 years ago a lot of research has been done in order to make lighting installations more energy efficient as well as to improve the visual capacity for people.

During the past ten to fifteen years, we have also seen a profound advancement in our knowledge of how light influences health and wellbeing. Due to the findings of this research, we know also about the definite correlation between different parts of the light spectrum and their effects on the body.

The spectrum of daylight changes throughout the day and affects the daily rhythm of sleep and wakefulness, what is called a circadian rhythm. Good and stable circadian rhythm improves the health and wellbeing.

For the active day and night period, the spectrum should be as much similar as possible to two attached examples. Both contain the important part of blue light and have an even spectrum for good visual performance. Important for the "healthy" effect is the light between 455 and 480 nm. For the resting/sleep period, this part should be diminished since it is suppressing the production of melatonin – "the sleep hormone". Hence, indoor light spectrum for evening's spectrum like "night spectrum" is favoured.

It is essential that the bid includes diagrams of the spectral characteristics of the selected LED light sources, since only colour temperature (CCT) and colour visibility index (CRI) are not sufficient as a source of information.

It is also very important to stress that the curves are indicatory but are showing where the different power peaks should be in the spectrum, especially for "sky lights".

Flats and common areas are designed for older people, who due to age processes have specific needs regarding the perception of light which the Contracting Authority has taken into account at defining the requirements. At the same time the elderly people are susceptible to the occurrence of glare and stroboscopic effect caused by the inadequacy of the light sources. For that reason, where possible, lights without glossy parabolic raster and lamps fitted with diffusers should be provided.

Light source has to be LED. Any differences which shall be explained and proposed by the bidder must be approved by the Contracting Authority prior to submitting the bid. This applies to all proposed deviations from these requirements. Any changes will be communicated to all bidders.

Panels must have a good quality connection to the condenser with suitably high power for cooling the LED chips.

Colour temperature is given for each of the luminous element or the specification for the dynamic lighting.

The base price for each luminous element or specification must be specified in the tender; otherwise the Contracting Authority may reject such bid as incomplete, without any possibility of the bidder's opposing this. It is recommended that the price includes the presentation of division onto housing, electronic elements and tubes (if there are any), as well as the cost of replacement components for the lighting failure. Within the individual light all the elements required for the installation and operation of the lamp at 220V should be offered.

Casings and profiles shall be matt aluminium, where the housing is made of aluminium. Steel housing is powder-coated in white.

Lights must be provided with certificates: certificate of degradability, IP certificate, IK certificate, declaration of conformity of the manufacturer, the CE certificate.

Before selecting the most favourable bidder, the bidders will be required to present upon the Contracting Authority's request a sample of each type of lighting in order to approve quality and optical properties as well as luminous efficiency, distribution and glare of the lights.

For the lights such a distribution of brightness is proposed which can to a lesser extent be adjusted by the bidder with respect to its programme. The technical requirements also give indicative expected shapes of the lights. In the event that the offer includes lights with a significantly different form, the bidder is obliged to notify the Contracting Authority with an explanation as soon as possible. The Contracting Authority will on the basis of tender's judge and decide whether adjustments are acceptable. The Contracting Authority reserves the right to reject such unacceptable bid without a call for amendment or change of the bid.

3.2. Illumination and Lighting

For the location in Izola the successful bidder will have to supply the latest products at the time of delivery for the bid price.

Lighting levels in all the spaces are according to SIST- EN12464–1.

In order to verify the adequacy of the offered luminaires, tenderers may calculate illuminance in accordance with these instructions: Calculations should be made with a factor of maintenance 0.8 and with a high indirect light setting. As this housing project is intended for older people who are particularly sensitive to glare, glare free lighting with UGR less than 19 is mandatory.

The specified form and dimensions of the luminaires are merely illustrative – more important is the distribution of light and efficiency.

For those spectra where the C-lambda curve is noted (Melatonin suppression) the total power within this part of the spectrum as well as the power at the 460 nm peak should be given in [mW].

The colour temperature and number of MacAdam, but max 3, should be given.

"Since flicker could be causing serious health problems for a group of people like photosensitive epilepsy, migraine and impaired visual performance, the LED fixtures should in principle be flicker free. The percent flicker and flicker index metrics should be given as well as frequency, amplitudes, waveform and modulation."

Luminaires should use LED with spectral distribution which stimulates circadian rhythm, Figs.1,2.

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Light & Engineering
Vol. 27, No. 5, pp. 9–14, 2019
https://doi.org/10.33383/2018-073

SENIOR LIVING – LIGHTING, CIRCADIAN RHYTHM AND DEMENTIA II[1]

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ABSTRACT

Light has always been an important part of human nature and development process. The on-going studies of light having an impact on human bodies are discovering astonishing facts. These facts show that the light has an effect on human bodies and can help reduce diseases and improve health. It is proven that the skylight can help substantially in this process, and our client decided to achieve a similar effect with the use of an artificial light. The development of such light involved a lot of a background investigation on what prospect of the light has the biggest effect on the human body. A nursing facility for elderly people was the first project where we installed such lights and the results are showing evidence of the light impact on human hormones.

Keywords: circadian rhythm, luminaire development, spectrum analysis, project measurements

I. EFFECTS OF LIGHT

Until recently, the biological implications of light and the light spectrum have not been a matter of interest for the producers of lighting fixtures. This has changed with a recent research which showed a very strong connection between the quality of light and health [1,5,7]. Effect on health can be traced throughout the history, and it wasn't until less than twenty years ago, though strong evidences of daylight's profound effect, that a brief understanding of this process arose [6].

Just until a few years ago the main interest of the lighting industry was "only" how to make the most energy efficient lighting in order to satisfy the visual needs or what is nowadays known as "Image Forming" process (later IF). Gradually, however, the attention also focused on "Non-Image Forming" processes (later NIF), since it became clear that they also are affected by light. By a deeper understanding of how the human vision works, the knowledge on both matters has increased. It became apparent that what was satisfactory for IF was not satisfactory for NIF, and the need to develop a lighting that satisfies both processes has become increasingly important [5].

However, there are only a few projects in practise that require solutions and spectrums for those two biological, but different processes – the visual IF and the circadian rhythm NIF, and there is yet no generally accepted standard to lean against.

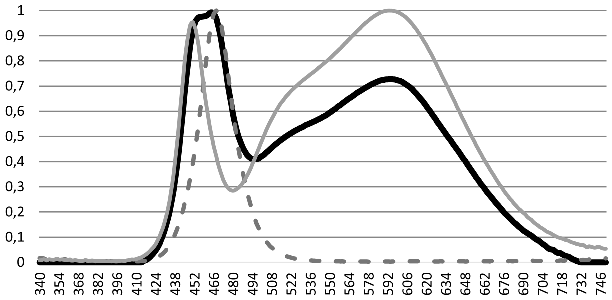

Fig. 1. Relative Spectral Irradiance

[1] Editing and styling by Elena P. Emelyanova, senior lecture of Institute of Linguistics and International Communication at I.M. Sechenov First Moscow State Medical University

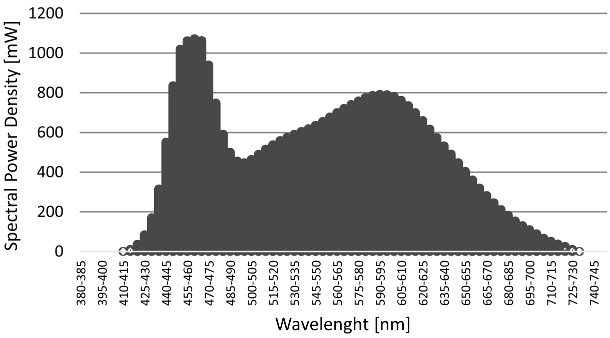

Fig. 2. Spectral Power Density

When you are suddenly faced with client's requirements for both, you have to start investigating. You begin by developing first the spectrum of the light source and then the optical features of the fixtures for both IF and NIF so that the optimal effect should be obtained [10].

2. LUMINAIRE SUPORTING NIF

2.1. LED Spectrum

Let's have a look at the light spectrum first. The subject matter on what is required for the visual need, IF, is well researched and the light sources are developed mainly to satisfy this need in an optimal way. There is, however, significantly less data for the NIF, although a lot research has been done to form a solid base to work on. The most important and the very basic result of this research is that the light spectrum should contain enough energy within the action spectrum for melanopsin which has a peak between 455 nm and 490 nm. Since this spectral band is not of great importance for vision or the colour rendering index, LED and chips manufacturers do not have a broad choice of chips emitting this part of the spectrum. This means that one

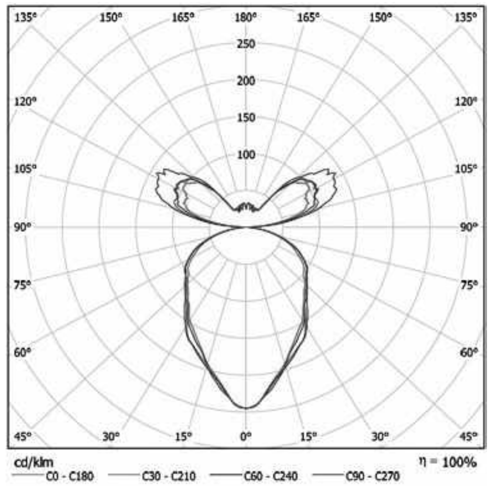

Fig. 3. Photometric results SKY LUM

can find/develop a satisfactory light engine only by combining various chips [3].

Considering NIF requirements and the process of hormone melatonin suppression and also rerelease of its secretion, we are looking at two corelated colour temperatures (CCT) of the light. For the evening and night time we require the spectrum with low energy emitted inside of C-lambda curve, so we need the light CCT from 2,700 K to 3,000 K. The tricky part comes when we want to have both good IF and NIF effect. For such examples, we need "colder" CCT, but most importantly, a high light energy emitter inside C- as well in V-lambda curves. We know that the ganglion cells are photosensitive and are mostly connected to blue cones. This means that the best effect on melatonin suppression will be in a narrow wavelength band of the blue spectrum. We need to combine two LED to satisfy both IF and NIF effect. By conducting a major research of the LED on the market. which can support the theoretical principle of NIF effects, we came up with a solution that completes the suppression and the secretion of melatonin in a most sufficient way. This result shows that the activation factor that we reached is 0,68 which is higher than most of the extreme cold white CCT solutions on the market.

$$a_{mel,v} = \frac{X_{e,mel} = \int_{\lambda_0=380nm}^{\lambda_0=580nm} X_{\lambda} * S_{mel}(\lambda) * d\lambda}{X_{e,\ vis} = \int_{\lambda_0=380nm}^{\lambda_0=780nm} X_{\lambda}(\lambda) * V(\lambda) * d\lambda}.$$

The grey line on the Fig. 1 presents the white LED of 4,000 K, while the dotted line presents the blue LED with a peak value of 468 nm. The CCT at

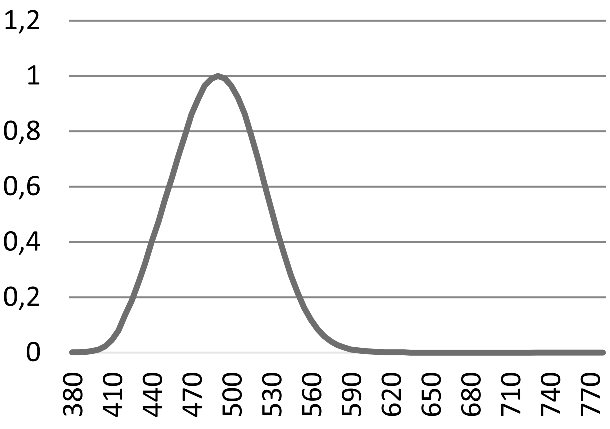

Fig.4. Melanopic curve

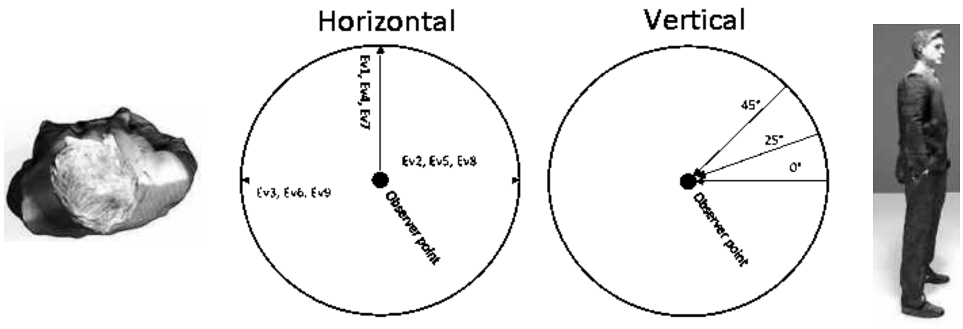

Fig. 5. Measuring points directions

this combination results in 5,300 K, and shows an interesting increase of the colour rendering index from 80, which we got from standard white LED of 4,000 K, to 91 just by adding the monochromatic blue LED. This results in an efficient solution for both NIF and IF processes. Energy emitted in interval of (455–480) nm was 5,016 mW with peak spectrum power density, Fig.2, at 465 nm, 218 mW/nm. This represents enough energy to suppress the melatonin, but the energy with this wavelength that we get from natural daylight is much bigger [8].

Although we are looking at the process of hormone melatonin, we need to take into consideration that when we are exposed to the achieved spectrum, the melatonin secretion will have to start before sleep. In this stage we need to change the spectrum to opposite, meaning we need to lower the spectral power density in wavelengths from 380 nm to 580 nm, resulting in use of LED with lower CCT of 2,700 K to 3,000 K.

However, the efficacy of a luminaire like this cannot be compared with a standard LED luminaire on the market. Using monochromatic LED with luminous efficacy of only 25 lm/W, we can reach the maximum efficacy from the luminaire to only 95 lm/W for the achieved spectrum. The warm white colour luminous efficacy, however, can reach up to 115 lm/W. When developing this kind of the luminaire and the spectrum we also have to understand the background of the process that is happening inside the human body's circadian clock.

2.2. Luminaire Photometry

The second step in developing the luminaire is optical photometry, which must be satisfactory for both the IF and NIF. Luckily there are some parameters that go for both – no glare, no flicker, and no large variations in luminance within the field of view. This can be achieved with large light emitting surface where we need to consider direct as well as indirect lighting. The angles where the light enters our eyes is under 40° to 60° when exposed to natural skylight. These angles are affecting most of photosensitive ganglion cells and have an effect on melatonin suppression. The indirect lighting plays a very important role in achieving these angles. The second important thing about the photometry requirement is the low gradient between luminance on the ceiling and the luminance on the light emitting surface. For example, if we look at the downlight fixtures the gradient of luminance can reach 1:10.000, where with direct and indirect illumination this can be easily reduced to 1:40 or even below 1:10.

We chose to go with the indirect and direct photometric distribution where the ratio of up-light is 45 % and the down-light 55 %. The PMMA material with special laser printed pattern provides the batwing photometric shape on upper light and the narrow lambert on the down light, Fig.3.

The light is coming into the PMMA plate from the side, where the distance between Light Guide Panel and the LED diodes must be very precise. The distance for reaching minimal light losses should be from 0.4 to 0.8 mm.

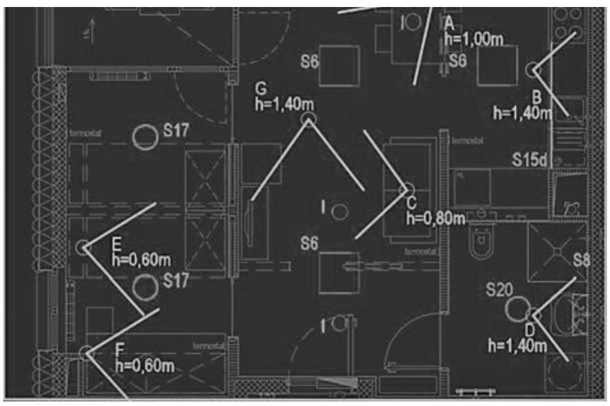

Fig.6. Measuring points in the room

Fig.7. SKY LUM ceiling lights providing low glare and minimalistic design

3. NURSING HOME PROJET

The product is called SKY LUM, and the first project was made for a nursing home. After a few months of using the luminaire, we agreed to make measurements where we were observing the illuminance at different angles and the Equivalent Melanopic Lux (later EML). EML is the calculation the flux emitted inside of Melanopic curve shown in the Fig.4. The concept of EML is discussed in American WELL Building standard and shows the amount of light that affects our circadian rhythm.

The measuring points were considered in three different conditions – as height of the eyes of tenants, angle for spectrometer device and the direction of viewing angle according to the tenant's position in the room, Figs.5,6

Below you can find examples of the measurements in the room, Table. They show the difference in the till angle of the spectrometer. Observing the values for point E, you will notice that the results are much different. This is caused by a classic ceiling fixture, with no increased blue spectrum for circadian light. The Melanopic ratio in this case is almost at half of the values comparing to the SKY LUM fixtures in the room.

4. CONCLUSIONS

The client request has challenged both the lighting engineers and designers. The challenge was not how to create the special spectrum, but to understand the NIF processes that are happening inside of our bodies. The amount of medical and technical

Fig.8. SKY LUM pendant luminaires provide low light gradient from the ceiling and the light surface, producing low glare and the right light angles for NIF processes

Table. Examples of the Measurement

Measuring angle 0°							
Measuring point	**Point height**	**Eh [lx]**	**Ev1 [lx]**	**Peak Wavelength [nm]**	**Energy [mW/ m^2nm]**	**EML [lx]**	**Melanopic RATIO**
A	1.2m	59	420	465.92	9.77	332.05	0.96
B	1.4m	1503.12	545.17	456.74	11.87	391.04	0.87
C	1.1m	548.63	371.62	465.92	8.27	285.61	0.94
D	1.4m	389.16	269.17	465.92	6.17	217.18	0.98
E	0.9m	403.52	229.87	606.13	4.79	101.52	0.54
G	1.4m	840.24	290.39	467.75	6.35	220.29	0.92
Measuring angle 25°							
Measuring point	**Point height**	**Eh [lx]**	**Ev4 [lx]**	**Peak Wavelength [nm]**	**Energy [mW/ m^2nm]**	**EML [lx]**	**Melanopic RATIO**
A	1.2m	591.7	673.61	465.92	16.3	549.67	0.99
B	1.4m	1503.12	659.35	458.57	14.31	494.27	0.91
C	1.1m	548.63	514.85	465.92	12.06	410.73	0.97
D	1.4m	389.16	375.39	465.92	8.8	307.92	1
E	0.9m	403.52	326.36	607.83	6.71	145.73	0.54
G	1.4m	840.24	334.38	467.75	7.7	263.11	0.96
Measuring angle 45°							
Measuring point	**Point height**	**Eh [lx]**	**Ev7 [lx]**	**Peak Wavelength [nm]**	**Energy [mW/ m^2nm]**	**EML [lx]**	**Melanopic RATIO**
A	1.2m	591.7	749.09	465.92	18.39	617.60	1
B	1.4m	1503.12	975.16	465.92	22.44	767.38	0.96
C	1.1m	548.63	597.94	465.92	14.29	484.40	0.99
D	1.4m	389.16	441.48	465.92	10.31	361.40	1.00
E	0.9m	403.52	392.6	602.72	8.06	175.52	0.54
G	1.4m	840.24	529.52	467.75	12.78	431.3	0.99

research reports on this issue is huge, but some of them can still be misleading. This might be because of weak (ground) basic understanding of the neurological and endocrinal facts by the researchers and the optical distribution of light from the installed fixtures [3,4,9].

The product that we successfully developed and installed in the nursing facility results in a new approach to using light which can help people that for different reasons cannot be exposed to adequate amounts of daylight. This is often due to insufficient number of personnel to assist and move elderly with handicaps. This spectrum has the effect of keeping the circadian clock in order, which has a positive effect on healing processes as well as improving the immune system, etc. The client Nepremičninski Sklad Slovenia (The Real Estate Fund of Pension and Disability Insurance) was pleased to build one of the first general projects in Europe that support the NIF processes through the artificial light. The measurement results show that lights are emitting the spectrum required, to have an impact on circadian rhythm. This confirms that we have succeeded in the development of lighting efficacy for NIF as well for IF processes.

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Light & Engineering
Vol. 27, No. 5, pp. 15–21, 2019 *https://doi.org/10.33383/2019-010*

LUMINOUS ENVIRONMENT AND THE PERCEIVED ENVIRONMENT[1]

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ABSTRACT

In lighting design, the main concept is to achieve a healthy environment, which addresses energy efficiency, cost, maintenance, and quality. User-friendly lighting systems shall be adopted to architecture and interior architecture. User control over the lighting system is important, by dimming or increasing light output, by changing the colour of the light sets the inner atmosphere and affects user mood. Standards and codes on lighting shall also be evaluated by means of these topics. The paper aims to analyse how the luminous environment is affective on the perceived environment. Hence, a series of experimental studies and recent research will be evaluated in regard to understanding and designing luminous environment.

Keywords: luminous environment, space perception, lighting standards, indoor lighting

1. INTRODUCTION

Lighting has a route from the luminous environment to the perceived environment, which covers many issues regarding lighting quality and quantity. By referring to the quotes by Cuttle (2003), the luminous environment is transformed into the retinal image, which is the stimulus for the visual process that provides information to enable the perceptual process to recognize objects and surfaces, which form the visual basis for the perceived environment [1].

This statement underlines the importance of measurable items such as the average illuminance on the horizontal or the vertical surface, or the luminance distribution on the wall surface, which lead to simple perceptions. However, the response to the immediate environment covers the non-visual effects of lighting as well. These effects can be grouped as higher-order perceptions [1]; they are the responses of long-term impressions (after spending a certain time in an environment). This process is highly dependent on our knowledge, background, experiences. In the studies, correlation methods are extensively used in order to define the effect of luminous environment on the perception of luminance, colour appearance, and illuminance.

The lighting design approach, which is based on the application of the European Standards such as EN12464–1 [2], shall also be discussed by means of the above issues, regarding non-visual effects of lighting. The critical components in visual comfort: illuminance, luminance, and the spectrum of the light sources are needed to be discussed by means of their interaction with perception, even human health [3]. The paper analyses recent studies and research on designing a luminous environment with respect to the perceived environment.

[1] The editors received several reviews of this publication, two of them positive, one reasonably negative. Nevertheless, the article is published because the issues of visual comfort, which have a long history of research and the non-visual effects of light, studied recently, in modern concepts require a unified approach to the design of lighting systems.

2. VALIDATING VISUAL COMFORT AND DEFINING EMOTIONAL SPACE

The method involves establishing a relationship between subjective judgments and light measurement. In these studies, the criticism of the accuracy of stimulation arises from the case of using scale models and/or computer-aided research methods, which are named as "abstract conditions". Flynn et al [4, 5] had important findings in the sense that they used real interiors and participants. Individual rating scales, which were related to each dimension (perceptual clarity, spaciousness, formality, spatial complexity, evaluative) revealed how lighting design influences space perception. They also evaluated the findings in the three-dimensional space derived from the MDS (multidimensional scaling) analysis. In 1979, Hawkes et al [6] studied a series of lighting installations and developed a map, which shows the location of the types of office lighting on two dimensions, interest and luminance, identified by factor analysis. They concluded on equal preference areas in regard to lighting installations.

There are similar studies, which try to evaluate the effect of the luminous environment on the perceived environment. In 1999, in the study conducted by Manav and Yener [7], 174 undergraduate students evaluated the impression of clarity, spaciousness, relaxation, privacy, pleasantness, and order (the subjective terms on which lighting design is a dominating factor). In a room where no daylight was available, cove lighting was supplied by fluorescent tubes (5400 K) and E_{av} = 270 lx, spaciousness and visual clarity was satisfied. Uplighting was preferred for the impressions of pleasantness, privacy, and relaxation, which was supplied by tungsten filament lamps with E_{av} = 110 lx. Wall washing was satisfied by fluorescent tubes (5400 K), E_{av} = 300 lx, and this system improved the impressions of visual clarity and order. Participants reported more positive feeling under warm light. However, in the study, no special question regarding the colour appearance of the surrounding objects/items was evaluated.

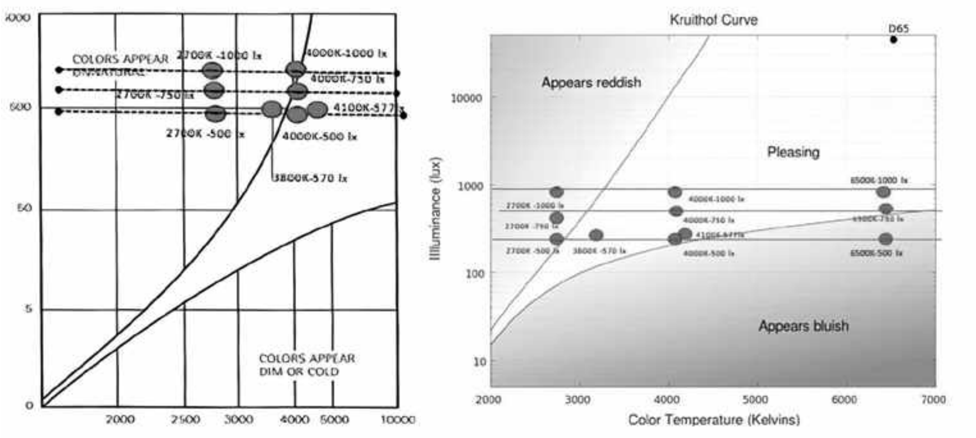
In a series of studies conducted by Manav [8], subjective impressions in regard to colour temperature and illuminance, 2700 K and 4000 K colour temperature for 500–750–1000 lx, were tested. The most suitable lighting scenario(s) were investigated in the study for offices. The results suggest that a change in colour temperature and illuminance has affected the visual appeal of that space. These findings are compared to Kruithof's curve (1941) in Fig. 1a [11] and Kruithof's curve (revised version) in Fig.1b. In both of the curves, 4000 K was better with respect to 2700 K for three of the illuminance levels: 500, 750, and 1000 lx. In the study, 4000 K was preferred to 2700 K for comfort and spaciousness, while 2700 K was suggested for relaxation, luminance and saturation evaluation.

While discussing space perception, the problem shall be approached by energy efficiency, the power of the electrical lighting system, as well as the emotional side, the atmosphere of the space. An experimental study was conducted for this purpose in [9]. In the study, the energy performance (quantitative data) and visual comfort (qualitative data) of tubular LED lamps versus tubular fluorescent lamps were reported. Technical data for tubular fluorescent lamps were as follows: 36 W, 3300 lm, 92 lm/W, 3800 K correlated colour temperature, and 570 lx (the maintained illuminance level on the working surface). Technical data for tubular LED lamps were: 20 W, 1600 lm, 80 lm/W, 4100 K colour temperature, and 577 lx (the maintained illuminance on the working surface). The space perception was evaluated by the following adjectives: spaciousness, wide, airy, and rested (relaxation). The responses were compared under both of the lamp types by SPSS17 statistical program, no significant differences were found by means of quantitative and qualitative data.

Fotios argued on the revised Kruithof's graph by empirical data [10]. He discusses that Kruithof is widely cited as a design rule and has been the focus of many experimental studies, however after 1990, in regard to the advances of the new technology, many empirical data are against his rules. The pleasing conditions are satisfied by avoiding low illuminance and do not favour any colour temperature.

In the present study, two curves, which refer to Kruithof's study, are discussed. Results of some experimental studies, which were conducted by the author and her colleagues, were marked on the graphs. It is seen that there are differences between them such as: 3800 K – 570 lx corresponds to positive subjective impressions according to the above study, it is under "pleasing" region according to the revised Kruithof's curve in Fig. 1b, however it is under "colours appear dim or cold" according to the Kruithof (1941) curve in Fig. 1a.

Similarly, when the other findings in the study conducted by Manav et al [7–9] are plotted



a) b)

Fig. 1. a) Evaluating visual comfort conditions by Kruithof's curve (1941); b) Kruithof's curve [11]

on Kruithof's curve, there are differences between the results. The experimental data in the study conducted by Manav [8], 4000 K – 500 lx, 4000 K – 750 lx, and 4000 K – 1000 lx were perceived as comfortable and spacious; these subjective evaluations are positive adjectives and they are short-term responses to the immediate environment. Though there are not identical subjective evaluations on the curve, these findings are tried to be matched to Kruithof's curve (1941); 4000 K – 500 lx combination is in the comfortable region, but 4000 K – 750 lx, and 4000 K – 1000 lx are on the line to the region of "colours appear dim or unnatural" region. Kruithof's curve (revised) support three of the lighting situations (4000 K – 500 lx, 4000 K – 750 lx, and 4000 K – 1000 lx) as being in the "pleasing" region.

Kruithof's curve is a tool for evaluating this relation, it gives a general idea. It is valuable as it suggests that there is a relation between colour temperature and illuminance for defining emotional space. Subjective judgments on the topic are not limited to being "pleasing" and "colours appear dim/cold" only as discussed in the works of Flynn et al [4–5], Hawkes et al [6], Manav et al [7–9], Knez [16], Veitch and Newsham [18]. Even today, new trends in lighting design lead us to discuss other issues such as tunable white light with LEDs, the light intensity on our eye and its effect on Circadian Stimulus, the influence of the light energy's wavelength on human bodily functions.

3. LIGHTING FOR TODAY

Today, regardless of the building typology, we always intend to achieve a well-designed, properly lighted interior space, which is "pleasing" and where we feel "comfortable". Though it is hard to have a consensus on subjective parameters such as visual clarity, relaxation, spaciousness, privacy (as they are related to subjective impressions), there are statistical methods to test and evaluate.

Starting from the beginning of the 21st century, in addition to the subjective impressions, novel issues such as light and health, human-centric lighting, circadian rhythm have become a topic of interest. A light beam not only passes through our eyes, which leads to seeing, but it also affects our hormonal activities and the rhythm of our body.

The well-known definition of circadian rhythm (to establish an internal replication of external day and night) and its influence on carrying an internal time information to all parts of the body, proves the fact of non-visual effects of light energy [12]. In case the immediate environment is dark, in the absence of light, the internal bodily signals continue to operate, but with a period more than 24 hours [13–15]. The external stimuli are necessary to activate the internal oscillator to 24-hour period. However, this might not be easy to satisfy quickly and immediately. A certain illuminance may not provide a signal to the internal oscillator to regulate the spectral sensitivity of the retinal photoreceptor. This fact may lead to the functioning of human metabolism inappropriately. Sleeping cycles, hormone activities, daily performance, immune system all are affected, which may lead to serious diseases. A lighting designer shall be a consultant to control these factors in order to satisfy a visually comfortable and healthy space.

Indoor lighting issues regarding visual comfort conditions are generally designed in reference to EN12464–1 [2], which refers to electric lighting systems. The Standard gives useful information in choosing and deciding on the size, as well as the location of the electric lighting systems. The required mean illuminance values on vertical and horizontal surfaces, Unified Glare Rating values can be calculated, luminaire position in accordance with working surfaces can be planned.

Research in the field suggests that lighting quality, which is described by colour property of light sources, human psychology, aesthetics, social and cultural factors, shall be considered in lighting design. However, lighting design is more than this, it has a power on human hormonal activities, personal wellbeing, immune system, performance as suggested by Bommel [3], Huiberts et al [12], Dai et al [13], Balia [14], Knez [16], Veitch [18].

In 2002, a novel photoreceptor in the retina of mammals was detected by David Berson, and we have learned that the effects of lighting quality is beyond visual effects. Light on the retina is the primary synchronizer of circadian rhythms. As we follow from recent research, there is a nerve connection between cones and rods in the eye and the visual cortex of the brain. The sensitivity between cone and rod systems varies with the wavelength of light, as well as colour of light. According to spectral eye sensitivity curves V', the human eye is not sensitive to extreme blue and extreme red. The eye has maximum sensitivity to green-yellow light. Research by scientists as Brainard [17] clarified that the sensitivity of the eye works differently than biological action curve. The sensitivity of the novel photoreceptor varies for different wavelengths (including light colour).

As the relation between the light spectrum and the human psychology is considered, it is seen that, though the visual sensitivity reaches its peak in the yellow-green wavelength region, the maximum biological sensitivity lies in the blue region. This difference shall be considered in lighting design because it is directly related to the non-visual effects of light.

A high-quality lighting installation goes beyond the visibility of the task and includes the visual appearance of the space [15–17]. Research on Unified Glare Rating (UGR) or Visual Comfort Probability (VCP) still continues. LED and/or other light sources with a higher colour temperature (stronger short wavelength content) cause more glare. Recent studies have shown that spectral glare sensitivity differs from spectral luminous efficiency function of the human visual system (with reference to the works of Fekete et al (2009) and Wördenweber et al (2007) as explained in CIE205:2013 [15] *Review of Lighting Quality Measures for Interior Lighting With LED Lighting Systems*. This fact leads to define the term Circadian Stimulus (CS), which is equivalent to percent melatonin suppression after 1-hour exposure to the light source.

In lighting design, it is important to consider illuminance according to the activity type, as well as the spectrum of light, exposure to a specific illuminant. In recent years, there is a consensus on evaluating the light incidence at the cornea. Two light sources may have similar colour temperature values, however, they might provide different Circadian Stimulus values. The difference is the result of spectral power distribution values. According to Figueiro [19] and her colleagues, it is accepted that light sources with higher colour temperature properties such as 5000–6500 K will generally provide greater Circadian Stimulus, however sometimes 3500 K sources have delivered less Circadian Stimulus than 3000 K sources.

Another important aspect in lighting design with respect to Circadian Stimulus is calculating the corneal illuminance (E_V) at the eye. Vertical illuminance is as important as the horizontal illuminance. Illuminance values are calculated in line with luminaires. This leads to select the most suitable luminaire type. It is advisable to use a direct-indirect luminaire system at the workplace [20]. Any lighting solution which can improve the visual ability with objective and subjective measures of alertness shall be developed and added to the surrounding. These designed items can be in the form of attached ones to the furniture (self-luminant office partitions) or self-standing ones such as light boxes, suspended ceiling with barrisol covering and automatic control system.

Another important item is related to lighting and ageing principles. It shall cover the visual needs of the user group. Eye detects and visual impairments shall be included in lighting design, as well as the circadian stimulus. Reports of Lighting Research Centre (LRC) on the topic highlights the power of illuminance, colour spectrum effect during daytime and night time as well. According to the findings of Figuera and colleagues [20], during daytime 400 lx / 6500 K combination or 550 lx / 2700 K at the eye for 2 hours is enough for Circadian Stimulus to reach 0.3–0.4, while during evening 50 lx / 2700 K combination at the eye for 2 hours is activating Circadian Stimulus to 0.1.

A series of experimental studies from 1970s until today and their scientifically sound findings highlighted the impact of the artificial lighting system on user performance and wellbeing [21–25]. However, the importance of daylight shall never be forgotten, it shall be adapted to the lighting system. The best of all is daylight, psychology, and physiology of lighting. Daylight spectrum and its effects on human being shall never be forgotten, always have to be added to the design.

4. DISCUSSION AND LIMITATIONS TO INVESTIGATE

CEN/TR16791 explains the spectral sensitivity of photoreceptors to assess lighting conditions with respect to their potential to achieve non-visual effects of light in humans [25]. Though it is difficult to measure non-image forming visual effects of light in humans, there are some recent findings. One of them is a research conducted by Koga Y. and Yamakawa M. [26], where the authors remark that vLEDs shall fit to mimic daylight; vLEDs are suitable for spaces and places, where colour aspects are a priority matter. Meanwhile, bLEDs render bluish colours despite the hue shifts. In addition, they suggest that bLEDs shall be selected when energy efficiency comes under photopic visual conditions. vLEDs have higher S/P ratios than bLEDs when the CCT is the same.

In line with the improvements in technology, new lighting solutions are reported. User-friendly lighting systems are adapted to architecture and interior architecture. Automatic controlled lighting systems, tunable lighting, user-centred design solutions are all technological improvements and design solutions which are frequently used.

In another study, energy performance (quantitative data) and visual comfort (qualitative data) of tubular LED lamps versus tubular fluorescent lamps are reported. Measuring and calculating illuminance, uniformity, power demand, total harmonic distortion, and power factor of tubular fluorescent and LED lamps allowed a comparison of the two lighting installations via quantitative methods. Qualitative data is evaluated by a visual task designed to evaluate the room impression and perception changes in the lighting systems. Results suggested that tubular LED lamps are similar to tubular fluorescent lamps in terms of lighting quality. The evaluated data on illuminance, glare, and visual appearance indicate that there is no difference in visual perception between lamp types. On the other hand, 22.8 % of energy-saving ratio could be achieved with the technology used in this field test; however, this ratio could be more than 60 % with inevitable development in LED technology [13]. The role of LEDs on Circadian Stimulus should be studied for similar settings and findings should be analysed from health-related issues.

CONCLUSION

The link between the stimuli (light energy) and the perception of space has been studied by many researchers. As the perception of the luminous environment depends on the adaptation of the visual system to the immediate environment, user differences, these factors shall be studied in lighting design issues. Simple perceptions (immediate responses) such as illuminance, luminance, and colour appearance show links to the luminous environment, whereas higher-order perceptions (spaciousness, complexity, visual clarity etc.) are more complex and need tenuous links.

While considering human responses to lighting conditions, it is recommended to satisfy:

- Not only horizontal illuminance (E_h) but also vertical illuminance (E_v), designing illuminance at vertical surfaces in addition to the horizontal surfaces shall be considered, light distribution in the space shall be designed and controlled;
- Luminance, as well as luminance contrast (in addition to general lighting, task lighting shall be satisfied), glossy reflections shall be controlled, shadows shall be considered, dark shadows which distract attention shall be avoided;
- Colour temperature of the light source (CT) is barely enough, spectral power distribution (SPD) shall be considered as well. Hence, colour properties of the surfaces shall be planned, colour contrast is important for visual acuity;
- Flicker (visual distraction and visual acuity).

The main concept should be to achieve a healthy environment, which addresses energy efficiency, cost, maintenance, and quality. User-friendly lighting systems should be adapted to architecture/interior architecture. User control over the lighting system is important for visual comfort, as well as circadian system. By dimming or increasing light output sets the inner atmosphere. Changing the colour of the light, as well as distribution, affects user mood, in other words, the space perception. Circadian stimulus effect should be considered at lighting settings as well.

The budget is another item to be considered in the process. Low-cost and quite effective solutions should be adopted to conditions. Integrating light colour to the colour scheme of interiors is another important design approach. For instance at offices, partition walls and/or work-stations can be self-luminous. Their colour can be designed. Red coloured partition may not suppress melatonin, hence 6500 K may suppress melatonin.

The importance of daylight shall never be neglected, it shall always be the first critical design task. However, in certain occasions, especially where no daylight is available, the question of "human factors, visual comfort, and lighting quality" always needed to be answered. Quality of lighting metrics shall be defined and included to the Lighting Standards such as *American National Standard Practice for Office Lighting* [21], *CIBSE, Code for Interior Lighting* [22], *CIE Standard, Lighting of Indoor Work Places* [23]. By taking the advances of the technological outcomes and systems, automatic control systems, human-centric lighting, tunable lighting, Circadian Stimulus effect shall be unified to lighting design. The lighting designer shall produce lighting solutions that provide sufficient luminance in the task area while enhancing the architectural/interior architectural features to provide some visually interesting parts.

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Light & Engineering
Vol. 27, No. 5, pp. 22–27, 2019 *https://doi.org/10.33383/2019-022*

RESEARCH INTO THE EFFECT OF PHOTOMETRIC FLICKER EVENT ON THE PERCEPTION OF OFFICE WORKERS

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ABSTRACT

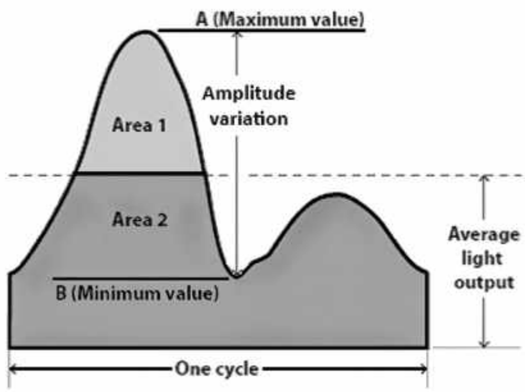
Today the number of office workers has reached to an enormous number due to the fast-growing technology. Most of these office workers spend long hours in enclosed spaces with little/no daylight penetration. The lack of daylight causes physiological and psychological problems with the workers. At this point lighting systems become prominent as the source and the solution of the problem. Photometric flicker event which arises in the lighting systems can sometimes become visible and brings a lot of issues with it. In this paper, an experimental work has been done to investigate the effect of flicker. For this purpose, the flicker values of 3 different experiment rooms for different lighting conditions and scenarios have been measured and a questionnaire study has been carried out in the experiment rooms with 30 participants. In conclusion, the effect of the flicker event on the volunteers have been classified and some methods have been proposed not to experience flicker effects.

Keywords: photometric flicker, indoor lighting, lighting scenarios, dimming

1. INTRODUCTION

The latest developments in the computer technology and the related technologies have increased the number of office workers and the working hours in enclosed spaces. A lot of different jobs, which requires different attention and concentration levels, have been done at desks in offices. There are some studies investigating the physiological and psychological conditions of the office workers who utilize little/no daylight during their shift [1–3]. These studies show that the effects vary from workforce loss to making critical mistakes.

A qualified lighting system requires a proper design with the light spreading internal volume continuously. Photometric flicker event causes physical impairments like eye strain, headache and finally desire to leave the place because of breaking this continuity, both under and over 60 Hz frequencies,



$$\text{Percent Flicker} = 100\% \times \frac{A - B}{A + B} \qquad \text{Flicker Index} = \frac{\text{Area 1}}{\text{Area 1} + \text{Area 2}}$$

Fig. 1. Photometric flicker percentage and index calculation [9]

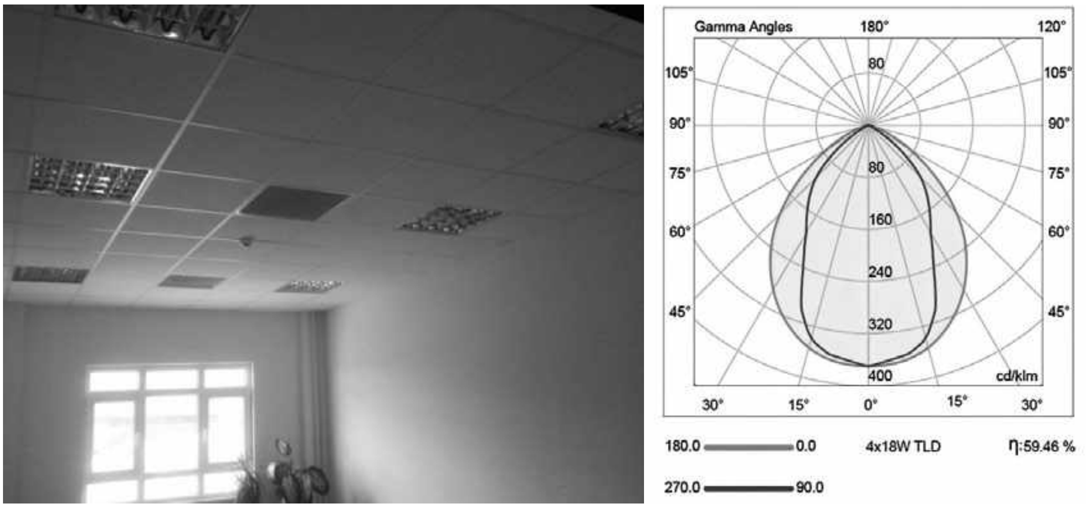


Fig. 2. Lighting system and light distribution curve of luminaires in Test Rooms 1, 2

even over 60 Hz light flicker is not possible to recognize by human eye [4–8].

There are common approaches worldwide to provide healthy lighting in an office environment by harvesting daylighting as much as possible like daylight responsive lighting control systems, dynamic lighting control systems and dimmable lighting control systems. However, flicker event occurs in all these lighting control systems especially in dimmable lighting control systems.

Flicker event can be explained in numbers by the graphic and the equations in Fig. 1. Flicker percentage and flicker index determines the qualification class of the lighting system. Flicker index takes a value between 0 and 1 while the flicker percentage between 0 % and 100 %.

Fluorescent lamps, a common type of discharge lamps, reaches to a 100 % flicker percentage with their electromagnetic ballast while this percentage decreases to 70 % with electronic ballasts depending on the specifications and brand of the ballast.

In this paper office workers are asked to do specific jobs in three different office rooms with different lighting scenarios. Then a questionnaire consist of 10 questions is made to the volunteer test participants about their psychological state during the period spent in the rooms. The lighting systems of the rooms are as follows: fluorescent lamps with electromagnetic ballasts for Room 1, fluorescent lamps with electronic ballasts for Room 2, LED lamps for Room 3. Five different lighting scenarios are applied in each room with 30 participants with clear vision: 15 female and 15 male aged between 18 and 40.

2. METHODS, MATERIALS AND RESULTS

Test rooms are office rooms on the third floor of M6 building in Engineering Faculty of Sakarya University. The coordinates of the rooms are 40º 74´ North latitude and 30 º 33´ East longitude. The surface areas of the rooms are 24 m^2 and each room have a window oriented to the northwest. The artificial lighting systems of Room 1 and Room 2 consist of six 4x18 fluorescent lamps and double parabolic mirror louver luminaries with the next characteristics (Fig.2):

Φ_v=3150 lm, *CCT*=4000 K, *CRI*=82, *UGR*=12÷15.

The only difference of the systems are the ballasts that luminaries have: electromagnetic ballasts in Room 1 and electronic ballasts in Room 2. In Room 3 six 1x41W, 60cmx60cm mid-class LED panels are used (Fig.3). All panels characteristics are the next:

Φ_v=4150 lm, *CCT*=4000K, *CRI*=84, *UGR*=12.7÷13.6.

The panels are connected to the dimmable DALI ballasts (92 % eff, pf=0.95). (All of the given data are provided by the supplier companies and verified by measurements)

The experiment begins with Visual Burdon Tests which takes 2 minutes of time. Burdon tests are frequently used to determine the attention and perception level of children and teenagers by demanding to point out a specific letter or image from mixed arrays. The participants are subjected to these tests after they spend 10 minutes of free time in the rooms. The tests are performed under 100 % operating con-

Table 1. Test Room Conditions

Room	Room 1	Room 2	Room 3		
Dimming	**100 %**	**100 %**	**100 %**	**75 %**	**50 %**
Illumination level (lx)	226	228	427	241	130
Flicker percentage	%91	%66	%9	%24	%62
Flicker index	0.49	0.21	0.02	0.07	0.19

Table 2. Burdon Test Results of the Test Rooms at Approximate Illumination Level

Room	Room 1	Room 2	Room 3
Dimming	**100 %**	**100 %**	**75 %**
Male Burdon Test Success	81 %	84 %	90 %
Female Burdon Test Success	83 %	85 %	92 %

ditions for Room 1 and Room 2 while 100 %, 75 % and 50 % for Room 3. After the tests are completed, the participants are asked to do an additional questionnaire to determine the effects of the test rooms on their psychological states. This questionnaire is prepared using Likert Scale like in previous similar studies [10]. As an effective attitude scale, Likert Scale uses a 5-scale response parameter set to questions as Strongly agree, Agree, Neutral, Disagree and Strongly disagree. Every single response has a numerical equivalent. As a widespread scale of attitude measurement, Likert Scale is a reliable scale preferred in a lot of scientific studies recently.

Table 1 shows that the illumination levels of Room 1 and Room 2 under 100 % operating conditions are approximate to the level of room 3 under 75 % operating conditions. Thus the Burdon test results of these conditions are evaluated separately. In Table 1, the illumination levels are measured values at working plane of 80 cm height by TES1336A luxmeter and flicker percentage and flicker index are the result of the measured values by UPRTEK MK350 tool.

As it is seen from Table 1, the worst flicker percentage and flicker index are arisen by electromagnetic ballast application while the best values are observed by LED panels with DALI ballast application at 100 % operating condition (no dimming condition). DALI ballast is also an electronic driving circuit which corrects the power factor. This specification of DALI ballasts and the LED panels working at DC voltage together decrease the flicker values and at 100 % operating give the best results.

In Room 3 the flicker percentage increased from 9 % to 24 % at 75 % operating and to 62 % at 50 % operating while the flicker index increased from 0.02 to 0.07 at 75 % operating and 0.19 at 50 % operating (Table 1). Since DALI ballasts drive by PWM modulation, the DC voltage waveform is clipped in proportion to the dimming. Thus, the

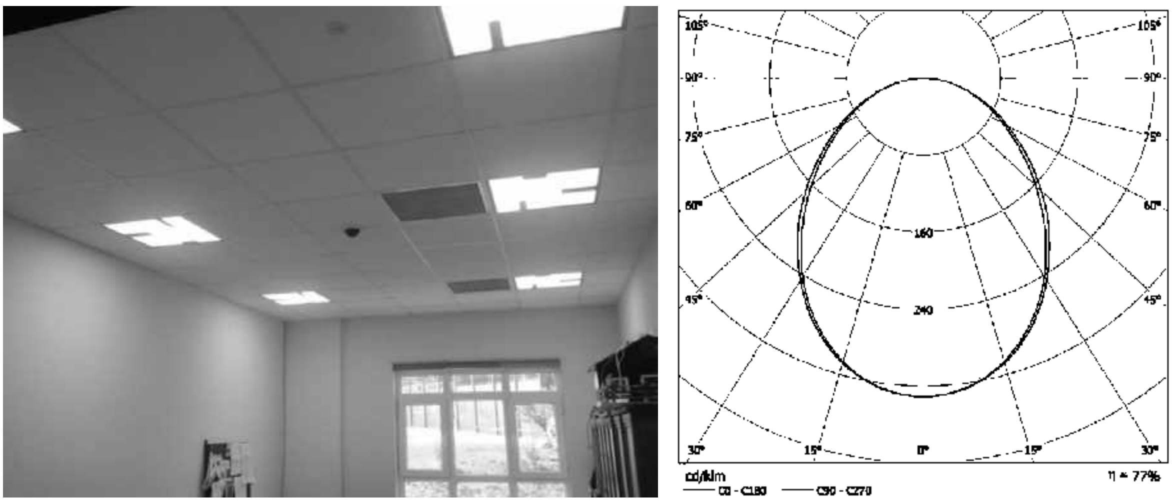


Fig. 3. Lighting system and light distribution curve of luminaires in Test Room 3

Table 3. Burdon Test Results for Room 3 at Different Illumination level

Room	Room 3	Room 3
Dimming	**100 %**	**50 %**
Male Burdon Test Success	92 %	87 %
Female Burdon Test Success	93 %	86 %

flicker values change by dimming conditions. In fact, the flicker values would be measured at higher levels, if the application is performed by an electronic ballast with no dimming property.

The Burdon tests and questionnaires are performed in dark hours when there is no daylighting effect. Table 2 gives the results of Burdon tests for the three test rooms at approximate illumination level and Table 3 gives the results for Room 3 at different dimming conditions.

Table 2 and Table 3 shows that the success in attention test in Room 1 and Room 2, where the flicker percentage and flicker index are high, are less than the success in Room 3 at the lowest illumination level. The success in Room 3 also decreases when the operating conditions are changed to 50 % with higher flicker values. Participants who should find and underline specific letters in the given texts performed more mistakes every time the lighting was dimmed. Those mistakes are not only made at the end of the Burdon Tests given but also at the top of the text. Participants could not perform the same success in the same tests in different tries under dimming and different light conditions. Thus, it can be concluded that the rise in flicker values causes perceptual disorder and distractibility even people are familiar to the work they are handling.

The results of questionnaires which evaluates the effects of the test rooms on the participants' psychological states are given in Table 4. The participants are asked eight questions in three main topics. All of the data entered to SPSS14.0 software and following tables are re-organized in the following form to create a better view to understand the results gathered by the questionnaire (Table 4).

As it is seen from Table 4, the number of participants with complaints of "feeling uncomfortable" and "being unable to focus" dramatically increases in rooms with higher flicker percentage and index values. In Room 3 the decreasing illumination level at 50 % operating condition also contributes the distractibility. The number of participants who are unwilling to work in the current lighting conditions supports the fact that the flicker values have significant effects on office workers' performance.

Table 4. The Feelings of the Participants in Different Lighting Conditions

Room	Room 1	Room 2	Room 3		
Dimming	**100 %**	**100 %**	**100 %**	**75 %**	**50 %**
Feeling uncomfortable in the room	11 participants (36.7 %)	7 participants (23.3 %)	1 participant (3.3 %)	1 participant (3.3 %)	3 participants (10 %)
Being unable to focus	10 participants (33.3 %)	8 participants (26.7 %)	1 participant (3.3 %)	1 participant (3.3 %)	5 participants (16.7 %)
Being unwilling to work in the room for a long time	13 participants (43.3 %)	10 participants (33.3 %)	1 participant (3.3 %)	1 participant (3.3 %)	5 participants (16.7 %)

Table 5. Participant Satisfaction Levels about the Visual Conditions in the Room "Q4. I am satisfied with the visual conditions of the Room"

		Frequency	Percent	Valid Percent	Cumulative Percent
Valid	Strongly Disagree Disagree	0 5	0,0 16,7	0,0 16,7	0,0 16,7
	Neutral	10	33,3	33,3	50,0
	Agree	9	30,0	30,0	80,0
	Strongly Agree	6	20,0	20,0	100,0
	Total	30	100,0	100,0	

Table 6. Total Median Values of Responses Given to the Questionnaire

Question	Q 1	Q 2	Q 3	Q4	Q 5
Median	4,00	3,96	3,62	3,82	3,72
Question	Q 6	Q 7	Q 8	Q 9	Q 10
Median	3,50	3,54	3,86	3,26	3,44

Table 7. Reliability Evaluation of the Questionnaire Reliability Statistics

Cronbach's Alpha	N of Items
,869	10

Looking at results obtained in Room 3, even under relatively high flicker conditions just 16.7 % of the participants have focusing problems and want to get out of the Room in a short time. Responses given to Questionnaire Question 4 is given in Table 5 as an example to understand the evaluations in a better way.

To investigate the total reliability of the questionnaire applied median values (Table 6) and Cronbach's Alpha (Table 7) should be investigated. As seen in Table 7, reliability of the questionnaire is 86.9 % according to the responses given by the participants. That indicates applied questionnaire to measure the psychological situations of the participants is a proper one.

3. CONCLUSION

In this paper the flicker effect on office workers is investigated by evaluating the Burdon tests and questionnaires performed with 30 participants who are asked to work under varying lighting conditions in three different test rooms. The results obtained from the tests and questionnaires show that people working in environment with high flicker percentage and index suffers from perceptual disorder, focusing problems and unwillingness to work for long hours in current conditions. It is found out that dimming at all levels also contributes the perception and attention issues. Thus, the lighting systems of an office environment should be selected to be able to provide high illumination levels with low flicker percentage and index. Some methods to decrease the flicker effect can be given as follows:

- Using LED panels instead of fluorescent lamps;
- Using ballasts and drives with high power factors;
- Using drives with current control methods instead of the ones with PWM modulation for dimming;
- If possible, determining the required illumination levels in designing stage so that no dimming scenarios are required and applied.

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Light & Engineering
Vol. 27, No. 5, pp. 28–36, 2019
https://doi.org/10.33383/2018-098

PUBLIC SPACE HUMANISATION IN THE NIGHT CITY

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ABSTRACT

Humanisation of public spaces is an important part of development strategies for a modern city. Design of a luminous environment plays a significant part in this process. We can see a correlation between the existing examples of human-oriented lighting of spaces and the scientific understanding of humanism. This helps us set a goal of space humanisation, select specific tasks that are solved by humanised public spaces, and define factors influencing humanistic quality of the environment at the phase of lighting design.

Keywords: humanisation, public spaces, city, lighting, human

1. INTRODUCTION

Humanisation of an urban environment as a living space of a human and a society has been an important issue for many decades. It has been drawing attention of architects, designers, as well as of researchers in urban, social, and psychological studies [1–3]. There is no exact definition to humanisation both in theoretical works of the past years and in modern researches that are focused on this issue. This term and its close definitions such as "human scale", "human-oriented approach", and "human centric lighting" are appearing in scientific papers, monographs, and reports focused on environmental design [4–6].

2. HUMAN SCALE OF A CITY

Development of a cityscape has been recently tending to offer more human-oriented public spaces [7, 8]. J. Gehl, with his huge experience, claims that urban design and urban planning should be used to bring a modern cityscape to a human scale, being a universal starting point. He believes that urban design and urban planning should stem from several scale levels: a large scale (multifaceted approach to a city, including quarters, activities, and transportations), a medium scale (quarters de-

Fig. Narboni, Godoy: a – São Paulo city centre, with illusive rivers; b – Valle de Anhagabau, final visualisation sign, location of public spaces and buildings), and a small scale (human landscape, i.e. human perception of a city) [8, p. 195]. According to Gehl, a small scale is extremely important, but often neglected both by customers and designers. He suggests that we must consider our five basic senses in relation to a cityscape and we should focus on landscape perception when we walk, not when we use transport.

Humanism of public places is often associated with a positive and interaction-friendly environment [3, 8, 9] that supports social activity and collective experience where citizens are satisfied with the quality of their lives and their environment.

The demand for night-time public places has increased because of changes in the way of life and in the social activity rhythm. Hence creation of a lighting environment that would satisfy demands of modern citizens and enable new activities for social experience is one of the most important tasks in development of a city strategy.

Luminous urbanism is a style of urban design focused on the main modern values: 1) human as a part of a social relationship system; 2) integration and mutual interaction of a human and an environment, natural and artificial.

3. LUMINOUS URBANISM

Luminous urbanism appeared in the 1980s in France. Now it is used in many cities around the world (in Europe, the USA, Russia, Africa, the Far East, and the Middle East) and is considered to be one of the most effective approaches to public lighting. It appeared after the role of lighting in a night city was reconsidered. Shifting from strictly practical and architectural lighting to design of a luminous environment in public spaces was the first step in development of luminous urbanism.

This brand-new strategy was first used when general lighting layouts were made for the French cities of Montpellier (1988), Lyon (1989), and Nantes, for the French communes of Évry and Brides-les-Bains, for the French town of Béziers (1992), as well as for the Scottish city of Edinburgh (1989)[1].

Urbanism as a whole and luminous urbanism in particular are notable for their inter-disciplinary concept and their multifaceted approach concerning manifold problems of a modern city and its citizens.

The concept of this direction in lighting design unites several methods which include: sociological, phenomenological, cultural, historiographical, and functional research methods, as well as psychological, physiological, and environmental research methods.

The multifaceted approach used in luminous urbanism includes huge studies at different urban environment levels: spatial, social, cultural, economic, technological, and environmental.

The inter-disciplinary nature and the multifaceted approach of luminous urbanism allow balancing between:

– Urban and natural landscape;
– Human and a city;
– Lighting solutions for various facilities of a night landscape;
– Local lighting of a facility (or a group of facilities) and a city;
– Lighting aesthetics and utility tasks;
– Individual and social properties;
– Conservative values and the future;
– Interests of authorities, citizens, and designers.

A bright example of luminous urbanism can be the 2011–2012 General Lighting Layout of São Paulo. The main task was to create a night landscape that would represent a unique Brazilian metropolis, the most populated city in the Southern Hemisphere. The combination of different architectural periods and various styles, different ethnic communities, growing districts, plenty of viaducts, tunnels, crossovers, which seem not to decrease traffic intensity and create a complex visual space layout in the Old City, composes an image of this industrial giant. Despite this, São Paulo shows high social activity at night.

The studies of the lighting environment showed: the current lighting does not meet the requirements of the city and its citizens; the general plan focused on practical lighting does not solve major problems of São Paulo [12]. Another approach was needed to unite all bright parts of the urban picture and to show a huge power of the night landscape.

The history of the city pushed the idea for the general lighting layout. There were rivers flowing through the historical centre of São Paulo many years ago. Their memories served as a lighting image to reproduce the majestic landscape with rising

[1] See [10, 11] devoted to the history, development, and future of luminous urbanism.

skyscrapers [12]. The story is connected with today (Fig.).

The illumination of various public spaces crowded by citizens and tourists complemented this poetic theme. The general lighting layout allowed to reduce energy consumption and at the same time to increase individual morphology of the city at the evenings and night hours [12].

Luminous urbanism is a strategic approach to lighting design based on the Human–Light–City system. Due to interrelations of all 3 components, we work on several directions. Each of these directions includes studies of public spaces, a luminous environment, and social problems. The main research levels are:

– Detail review of public spaces by day and at night considering their functions in urban development and their future changes;

– Highlighting buildings and structures that shape the night city considering their perception at close, medium, and far distance;

– Highlighting significant facilities in the city;

– Correlation of lighting options with geographical, natural, climatic, topographic, historical, cultural, and morphological features of the city [10, 11, 13];

– Revision of current lighting installations, measuring lighting properties, and their revision as per the existing rules of lighting [14];

– Revision of light pollution levels;

– Energy saving analysis;

– Revision and analysis of display lighting.

We create a set of tools and analytical recommendations based on this research: a united general layout of the urban lighting that is a kind of a map for the lighting strategy [10, 11].

The general lighting layout unites the diverse aspects of the lighting environment in a city: functional, architectural, and artistic lighting, lighting of public spaces, including municipal parks, gardens, squares, as well as festive lighting and display lighting. The layout includes future possible changes of the city on the one hand. These changes and appearance of new requirements, people's demands, new functions, and technologies on the other hand suggest regular reconsideration of the general layout.

Researchers and specialists in lighting design mark that participation of citizens is significantly important to create a general lighting layout plan [10, 11, 15].

4. HUMAN POTENTIAL

The attraction method for local community at different levels of lighting design is an effective tool for luminous urbanism (with studies of location problems and lighting development, as well as with test runs in urban environments). Participation of citizens in creation of a lighting environment is considered as a part of humanisation of public spaces at night.

First of all, communication with citizens allows you to understand current local problems and to examine these problems from the point of view of local people. Even a highest-level designer would make a subjective (but professional) assessment to a specific case that would not represent a broad picture of people's demands without any interaction with citizens.

Then local citizens represent a specific cultural community: as a country, a region, a city, and a social group (subculture). It means there is a developed set of values, traditions, customs, social norms, and rules existing in this community. It is a system that defines the way of life, behaviours, social relations, and processes. To create a lighting environment that is appropriate for these cultural and social conditions, you need to understand the specific nature of this culture.

After that, you need to get feedback from citizens, i.e. their reaction to the quality of a lighting solution, which is one of the main parts in lighting design. If urban lighting is something more than just a list of requirements for safety and efficiency, we must focus on understanding social influence of lighting and citizens' acceptance of public spaces and transform this to lighting design [16].

This article suggests that not only considering various aspects of night city life (or reaching reasonable compromise) is possible due to direct or indirect dialogue between researchers, designers, and citizens. The more important thing is that all citizens can actively participate in development of a night landscape in their city. Usual citizens become designers who transform the environment for themselves and other people. Such a participation in urban transformations makes them feel their significance and responsibility, grasp their feelings of a united community where the voice of everyone is important. This shows a level of humanistic community development as humanism is focused on positive changes in a human and in the world around [17]. We can see that development of modern cities depends on a level of humanism in a community.

Designers interact with citizens in different ways: meetings, city walks, workshops, interviews, surveys, seminars, etc. Each approach is efficient in problem solving in their specific ways. The increasing participation of a community in urban planning and the technology development suggests new research methods of emotional, psychological, and physiological reactions of people living in the environment.

For instance, eye tracking that has been used in interaction analysis for a long time shows its efficiency in research of significance for urban lighting. We conducted a research with eye tracking in the project "Model Development of the Lighting of Saint Petersburg". We studied significance of a lighting environment in streets, cross-walks, main buildings, and landscapes[2] [2]. The advantages of this technology are that it allows to correctly measure and to analyse a human gaze direction (of a driver or a walker) and to highlight problem areas of night city lighting. However, eye tracking does not displace other research methods because the received data does not allow you to explain why some human first stares at something. This research method is efficient if combined with other studies.

Many other methods, approaches, and models allow analysing emotional reactions, perception aspects, and social interacting experience in public places by day and at night: environmental psychology, mind mapping[3], empiric studies, etc. Despite their differences, they are all focused on reduction of psychological, emotional, and mental distances between a human and a public space, as well as on development of good conditions for human interaction, i.e. increasing humanistic quality of an environment.

5. HUMANISTIC QUALITY OF PUBLIC SPACES

The level of environmental humanism is a quality indicator that can be hardly evaluated as quantity. How can we evaluate the quality of humanism in this case? How can we define the level of humanism? Are such aspects as safety, comfort, ecology, and efficiency enough? What is the reason for environmental humanisation and what is the influence on life quality?

According to E. Fromm, let us repeat that humanism is an action oriented to a human and environmental transformation [17]. We conclude that humanisation of public places continues after design. An active phase of humanisation starts when people begin to use spaces.

One of the founders of humanism in design, V. Papanek, in his book *Design for the Real World*, suggested that the main task of design is to change the human environment and the things used by a human, as well as to indirectly change people themselves [18, p. 31]. The main function and the main goal of a humanistic public space are to increase the humanistic level in society. So, the level or degree of humanism can be defined by social experience of human relations to each other, their city, the nature, etc. [19].

A lot of examples can show the influence of public spaces lighting on the level of humanistic quality of life. To clear up the exact process of influence, the author analysed some of the examples concerning social tasks fulfilled by public spaces. According to that analysis, he selected a list of task solutions focused on increase in the humanism level. You can see the description below.

5.1. Value Reconsideration

Lighting does not only change the image of the city; it influences on human outlook and values [20, 21]. It encourages people to take care of the nature, their city, and the environment. This tendency now is one of the most important in luminous urbanism. It is also presented in specific parts of lighting design. Here are some examples for influence of lighting design on value reconsideration of a city and its citizens.

[2] The study was completed as part of the project "Model Development of the Lighting of Saint Petersburg within the period 2018–2030" in frame of "Combined Program of Development of Saint Petersburg as a Centre of Lighting Culture with an Outlook until 2050".

[3] Mind map is a smart instrument, a technology allowing to visualize the analysis of associative and logic connections as a diagram. There are different types of mind mapping: cognitive, associative, conception. See: Martin, B., Hanington, B. Universal Methods of Design: 100 Ways to Research Complex Problems, Develop Innovative Ideas, and Design Effective Solutions. Beverly: Rockport Publishers, 2012, 208 p.

The first sensor technology was used in reference to street lights in 2009 in Toulouse (France). This allowed lamps to detect warmth of a human body. The street lamps shone 2 times brighter sensing a coming pedestrian, and they returned to their previous state after 10 seconds [22]. This technology saves nearly 50 % of electrical power. It also struggles with luminous pollution. A usual pedestrian becomes a campaigner of natural beauty and ecology in a night landscape. The experience of Toulouse was supported in many other cities of the globe.

One more example of positive influence of illumination on ecology was shown in the German municipality of Dörentrup. Its citizens could control lighting in one of the streets a few years ago. Typing a specific code on a mobile device, a pedestrian could turn on lights for 15 minutes. The street was dark from 11 p.m. A local public utility estimated that it reduced carbon emissions by 12 tonnes per year [22].

5.2. Culturally Educational Aspects

Lighting can play a progressive part in public spaces in terms of culture and education. There are many examples of subtle and interactive influence of lighting on citizens that improved their inner worlds.

For instance, there was a project in Lyon (France) that united illumination, vegetation, and art photography (by Yann Arthus-Bertrand). Due to interaction of three components, such as light, art, and nature, a comfortable environment was created on the street l'Annonciade. The environment encouraged every citizen to feel as a desired guest in the "living room" of the city and to enjoy the modern pieces of art[4].

A unique cycle/pedestrian lane was developed in the province of North-Brabant (Netherlands). This lane was a modern representation of the Vincent van Gogh's works, an artist who lived there in the 1880s. The design of the cycle lane includes a lot of mosaic stones that absorb solar power by day and beam at night. They form a colourful lighting pattern that reminds of the Vincent van Gogh's picturesque manner. This project represents a unique public space where cultural experience of modern art and innovative solutions unite people and make an artistic image of a night landscape.

5.3. Attraction of Attention to Culture, History, Social Places, and Events as a Condition for Identity

The issue to save national, personal, and collective identities [23–25] plays a significant role in multicultural conditions of a modern society [26]. Lighting responsible for morphology of a night city allows highlighting main buildings, to make direct allusions, and to symbolically demonstrate common values. This factor directly depends on conditions for identity at different levels: national and cultural identities, cultural community, self – identity.

The wide range of lighting solutions that fulfil this function and other functions suggests both temporary lighting and long-term lighting. For instance, the project in Ghent (Belgium) for a medieval harbour shows a historical courage, builds a poetic environment, and makes this place a merry and beloved cultural area.

Lighting is treated as a powerful tool to highlight the historical and cultural area of the Old City within the 2013 General Layout, to save and develop the legacy of Toronto (Canada). The rest of the environment is less illuminated and fulfils a function of a background.

In 2012, at one of main Moscow (Russia) highways the New Arbat, a project presenting lighting capabilities of bright mosaic panorama of the night city was realized. The modest colourful lighting frame located on high-rise buildings highlighted the identity in the contextually complex urban environment and made a unique space that united different historical periods.

5.4. Correlation with Dynamic, Location, and Nature of Social Processes

Lighting can be an efficient method to solve problems that are connected to changes in a daily activity schedule and functions of public spaces. Well-illuminated public spaces are overcrowded at night. Poorly-illuminated or non-illuminated spaces that could also become public centres are almost empty, which can deprive citizens of social interaction and spare time activities after dark. Besides, one space can play different roles by day and at night.

[4] The project was submitted for the 10th Anniversary edition, city.people.light award 2003–2012.

Lighting and smart technologies allow us to adjust urban areas to changing life conditions and demands of modern society. They transform functional and aesthetic criteria of public spaces [27, 28] to save their attractive image for people.

The function of single parts of lighting corresponds to changing conditions of urban areas and depends on time and area as for the General Lighting Layout of Xian (China). In addition to this method of lighting management: duration, sunlight intensity, purposes of outdoor spaces are also considered [29, p. 40].

5.5. Positive Influence on Psychological and Emotional State

The influence of lighting on psychological and emotional state and human behaviour has been recently studied by lighting design specialists. This influence is significant to ecology and human physical health, as well as to spiritual and moral health of a human and a society. Lighting in this case plays a significant role in humanisation of public spaces, cities, and their citizens.

The study of lighting influence on people is conducted in research institutes of different countries. For instance, the Eindhoven University of Technology (Netherlands) studies the possible usage of dynamic lighting and landscape design in wind-down of antisocial behaviour (decrease of excitation level, mood improvement, shift and growth of attention, social behaviour relief, self-consciousness and self-control increase) [30]. The project is planned in one of the entertaining districts of Eindhoven (Netherlands).

The study of art therapy of lighting in urban environment is conducted at the ITMO University (Russia). A combination of light, colour, and sound for audio-visual relaxation enables to differently use lighting and to improve the life quality in a modern city [31, 32].

The project implemented in the Netherlands is one of the examples for practical use of lighting. R. Teunissen created a social lighting sculpture (*Broken Light*) for Rotterdam. The sculpture dramatically changed the environment and the attitude of citizens to one of the streets that used to be known as a dangerous and criminal place. However, street Atjehstraat is now a social and cultural public space[5].

5.6. New Communicative Culture and Intercultural Communication

Urban lighting has a great potential that forms a basis of a new communicative culture based on overcoming social disintegration and alienation, on finding general concepts, values, ideas for representatives of different cultures and subculture communities, saving their identity [33–35].

The dynamic and interactive capabilities of lighting design play a significant role in public spaces that are used, as a rule, for temporary projects. There are diverse examples of such interactive lighting events in the world practice. You can see some of them below.

The famous *Marling* project (by U. Haque) was implemented in Eindhoven (Netherlands) in 2012. This performance reproduced live voices of citizens and made visual images of urban collaboration displaying diverse options of such interactions. The show was fascinating, but the main purpose of the project was new ways of communication and participation of people in changing their environment.

The *Treasure Hill* art installation was created in Taipei (Taiwan, China) in 2015 by I-Ju Pan. The installation suggested an active interaction: citizens are participants, authors, and spectators of a unique illuminated show; they manage colour and speed of light streams with special software.

5.7. Intuitive Navigation

We live in a heterogeneous and constantly changing world which includes a lot of connections and interdependences that go through endless information flows and processes of different nature. In this case, different ways of flexible structuring in any environment (social, media, urban, informational, etc.) are especially important. V. Papanek, a designer and a humanist, once said: "Design is a cognitive and intuitive effort to make a significant order" [18, p. 4]. Lighting design from this point of view should encourage humans to feel their moral certainty (arrangement) despite of the heterogeneous environment. This task suggests both physical space orientation and creating a specific psychological situation where humans realize their leadership (which is one of humanism conditions).

[5] The project was submitted for the 10th Anniversary edition, city.people.light award 2003–2012.

Cities Alive: Rethinking the Shades of Night describes the lighting layout of the London Olympic Park (UK). The plan affirms the efficiency of the intuitive navigation method. The lighting plan of the Olympic Park is based on nodes and highlighted destinations combined with lighting pedestrian lanes. The reaction of people to illuminated and non-illuminated parts allowed programming of the Park public space that could naturally manage people's streams. One of the purposes of the authors was to create an intuitive navigation environment [29, p. 31].

6. CONCLUSION

Humanisation of public spaces is a main part of development in modern cities. Environmental development and lighting design now play a significant role. The level of humanism in a public space is a quality indicator. That is why one of the main tasks of modern design is to find and to arrange quantitative approaches that could form this quality together. These quantitative approaches should consider the following factors:

– Correlation of lighting to specifications of social processes and human behaviour;
– Different user groups and their problems (demands, requirements, expectations);
– Need to decrease conflicts and antisocial activities;
– Environmental changes, natural and urban, in short and long terms;
– Cultural and educational function of lighting;
– More popular social demand for new communicative culture as a way to overcome social disintegration and alienation;
– Social request for human interaction and urban environment.

These approaches allow managing the process of public space humanisation and to make this process more stable.

E. Garin, an outstanding researcher of philosophy and culture of Renaissance, highlights that the basic principle of humanistic world view is the principle of balanced combination of personal matters and social matters that is established at the rise of high self-identity [36]. Considering this principle in reference to lighting design, we conclude that humanisation of public spaces is not just yet another approach to design, a working method, or a fashion. It is not just about improving and creating a comfortable, secure, and green environment (these factors are absolutely important, and they have to be considered by default). Humanisation suggests creating such a physical and psychological environment and such conditions that would encourage people to get social experience and interact with each other, the world, nature, and themselves. This social experience is based on people understanding themselves as personalities that possess a unique set of qualities and take a positive, pragmatic, and responsible stand to themselves, their society, the world, and nature [19]. In other words, the level of humanism is indicated by mentality, the way of life, and the manner of people that live in this environment. Humanisation of public spaces means both the return of the city to its people [7, p. 13] and the return of people to themselves.

The care of ecology, psychological comfort, and health, the interaction with other people and the city should be presented through conditions that motivate people to develop their humanistic qualities and offer a space to show these qualities. Lighting design and environmental development improve the quality of life and indirectly improve the human nature.

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Light & Engineering
Vol. 27, No. 5, pp. 37–42, 2019 *https://doi.org/10.33383/2018-106*

OPERATING CONTROL OF PHOTOBIOLOGICAL SAFETY OF LED LUMINAIRES

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ABSTRACT

Photobiological safety has become an integral part of safety requirements to general use luminaires including during certification. In that context, the necessity to control this parameter in the course of designing and manufacturing of lighting devices (luminaires) as well as sales of imported devices in the Russian market has increased dramatically. In the meantime, experimental assessment of this indicator in accordance with requirements of IEC62471–2013 standard is rather hard requiring application of special equipment and certified personnel. This circumstance makes operating control of photobiological safety by manufacturers almost impossible.

The foreign practice of application photobiological safety-related standards confirms this problem. In 2014, International Electrotechnical Commission has published a handbook for application of the standard provisions, which significantly simplifies the procedure of such assessments: IEC/TR62778:2014.

The article describes the method of application of provisions of this handbook as an operating tool in the course of development of general use LED luminaires with white light LED. The provisions consist of assessment of hazard level in terms of illuminance in the area of the most possible location of a spectator and colour characteristics of a light source.

A calculation method of risk level assessment on the basis of spatial light distribution and correlated colour temperature of LED luminaires is proposed, the results of calculations are compared with the results of laboratory testing.

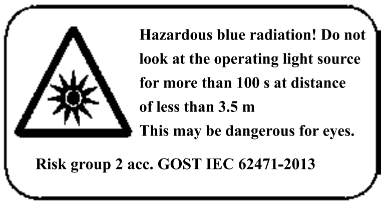
Keywords: technical regulation, photobiological safety, light emitting diodes (LED), blue light hazard, public health, quality control, performance test, testing techniques, risk groups, information for consumers

RELEVANCE

On the end of 2016, the decision of the Board of the Eurasian Economic Commission on supplementing the technical regulation of the Customs Union "On Safety of Low-Voltage Equipment" (TR CU004/2011) with new requirements to lamps and lamp systems photobiological safety, namely the requirements of standard IEC62471–2013 ("Photobiological Safety of Lamps and Lamp Systems"), has come into effect as the GOST R in Russian Federation. Therefore, in the course of analysis of safety of application of contemporary lighting devices (LD) and installations, participants of professional lighting engineering market, supervision authorities, public organisations and consumers of products should assess, take into consideration and warn about availability or non-availability of any risks in the area of photobiology.

Wide use of LED light sources in LD makes this issue especially relevant. In 2010, the report by *ANSES* (*French Agency for Food, Environmental and Occupational Health & Safety*) [1] expressed concerns on possible consequences of application of LED for illumination. By now, the global experience and scientific and applied studies by various

Table 1

Risk group	**Risk level**	**Exposure**	**Additional labelling of product**
0	None	No photobiological hazard, since there is no retina-hazardous blue radiation for more than 10,000 s (about 2.8 h).	Not required
1	Low	No photobiological hazard with normal behavioural limitations, since there is no retina-hazardous blue radiation for 100–10,000 s.	Not required
2	Medium	LD does not cause hazard of discomfort since there is no retina-hazardous blue light for 0.25–100 s.	 Information to be included in the documentation: WARNING! This product may emit hazardous optical radiation. Do not look at operating light source. This may be dangerous for eyes.

specialists have allowed in a more systematic and balanced manner to assess the risks of LED application. In June 2018, *SCHEER* (Scientific Committee on Health, Environment and Emerging Risks) approved the report [2]. On the basis of its analysis, which appears to be deep, the Committee made a conclusion on non-availability of evidences of adverse impact of LED on public health during normal use. Russian researchers draw similar conclusions [3].

In the meantime, in accordance with the standard IEC60598–1:2014 (“Luminaires – Part 1: General requirements and tests”), since 2014, the international practice of general use luminaires safety assessment includes requirements for assessment of *the blue light hazard* level, radiation within the region of λ in range (400–500) nm. The radiation of this region may cause photodamage to eye retina [4, 5]. In accordance with this standard, in the course of assessment of hazard degree (HD) of LED-based LD, it is necessary to follow the provisions of the regulation IEC/TR62778:2014 (“Application of IEC62471 for the assessment of blue light hazard to light sources and luminaires”), including those related to the proposed simplified method of assessment of hazard on the basis of illuminance level in a control point.

In general, the method of assessment of compliance of LD (luminaire) with the requirements of IEC/TR62778:2014 includes the following stages:

- Determination of the risk group (RG) of LED radiation (usually by means of a series of illuminance and/or radiance measurements in accordance with testing methods described by the regulation);
- Confirmation of the fact that the product has relevant RG confirming signs on the body, information of the same in the specification and user’s manual;
- Elaboration of testing report documenting compliance of LD with requirements of IEC/TR62778:2014 and IEC60598.

The method is of huge practical importance. The manufacturers (sellers) of LD have obtained an instrument for operating control of compliance of products with photobiological safety requirements and capability to use a report for declaring of general safety of a product. According to data of developers, the accuracy of obtained estimations is 15 %, which may be considered acceptable.

Table 2

Range of T_{cc} values of the light source, K	Threshold illuminance in the point of spectator's eyes location, lx, not more
< 2350	4000
$2350 \le T_{cc} < 2850$	1850
$2850 \le T_{cc} < 3250$	1450
$3250 \le T_{cc} < 3750$	1100
$3750 \le T_{cc} < 4500$	850
$4500 \le T_{cc} < 5750$	650
$5750 \le T_{cc} < 8000$	500

IEC/TR62778 PROVISIONS PRACTICAL APPLICATION METHOD

Testing engineers of the Central Plant Laboratory of MGK Light Technologies, confirming compliance of the products with the photobiological safety requirements, alongside with testing of LD (luminaires) in specialised testing centres, entered the IEC/TR62778 method into everyday practice.

According to IEC62471–2013, IEC62031–2011 standards and IEC/TR62778:2014 technical requirements LED-based LD are categorised into 4 RG on the basis of photobiological hazard of their radiation (upon the "blue light hazard" criterion) (Table 1)[1].

The goal of photobiological safety check of general use LED-based LD is categorising it as one of the safe RG: RG0 or RG1.

In case the RG2 hazard level is reached, the condition of the most probable installation of LD in a facility in relation to possible spectators with which the condition of safe RG1, the border of RG1/RG2, is defined. This information should be placed on the body of LD in a form of a special sign as well as in supporting documentation.

In Table 2, the thresholds of illuminance in the point of location of spectator's eye in a plane normal to the direction to light source depending on the value of T_{cc} (IEC/TR62778:2014) defining the upper border of RG1 are listed.

According to provisions of IEC/TR62778:2014, the manufacturer (seller) of a specific LD defines the most probable position of a spectator where occasional irradiation of eyes by the light from LD is possible provided the LD is located in its designed location. This method was included in the industry standard of the Association of Manufacturers of LED and LED-Based Systems (APSS) as a method of evaluation of photobiological hazard of LED-based LD [6].

THE RESULTS OF CALCULATION AND EXPERIMENTAL EVALUATIONS

We reviewed the most possible spectator position scenarios and gave an example of assessment of hazard of LED-based LD blue light impact

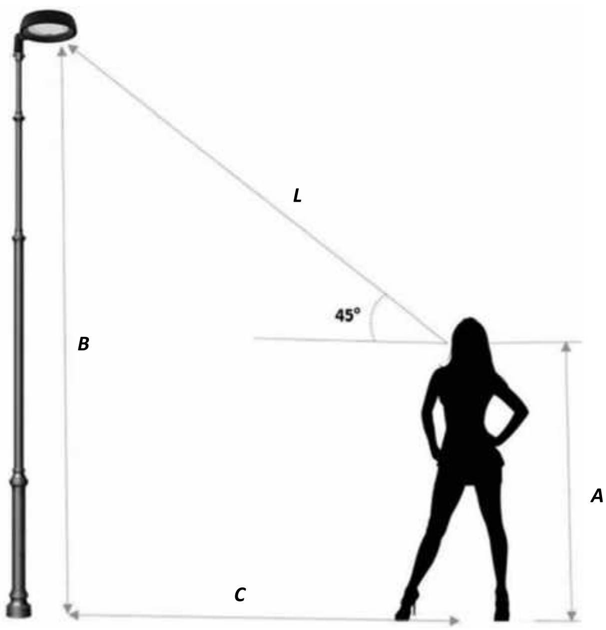


Fig. 1. Scene of the most probable position of a spectator in the illumination area of external LD

[1] Photobiological hazard of general use LD compliant with RG 3 is of low practical probability and is not considered in this case.

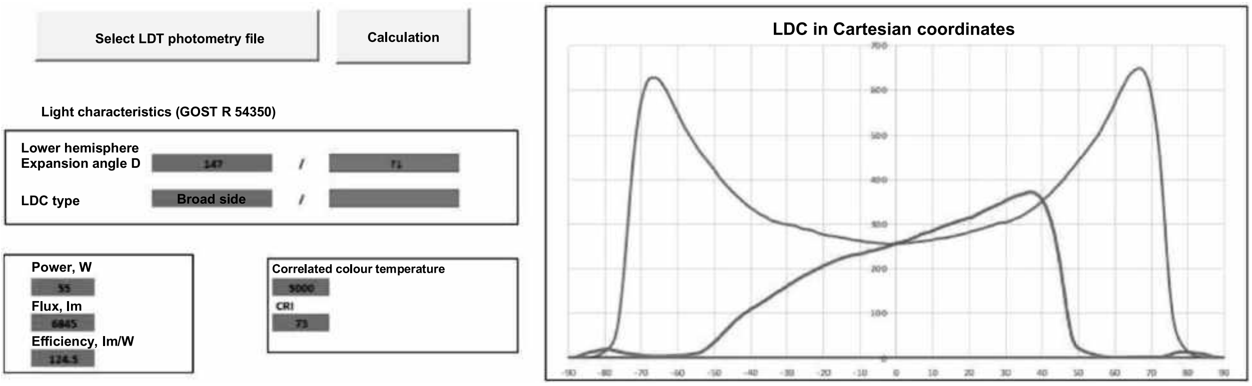


Fig. 2. Interface of the software for estimation of the level of photobiological hazard and light intensity distribution of LD (luminaire) in Cartesian coordinates (CCT – correlated colour temperature, *CRI* – general colour rendering index, R_a)

on human organ of sight on the basis of the IEC/TR62778:2014 method.

Let's review an example with a console LD for lighting of gardens and parks (Fig. 1):

- The LD is placed on a support at height of B = 4 m;
- The LD is based on a LED with T_{cc} equal to 4000 K in the first case and to 5000 K in the second case.

Intrinsic error of illuminance meter is within the range of ±10 %. The values of chromaticity of the reviewed light sources for general use LD are similar and the light of both LD is white. In that respect, possible error of white light illumination measurement with different values of T_{cc} does not significantly affect the intrinsic error of the illuminance meter.

In terms of light effect on the spectator, the most probable position of the latter is at some distance C from the support of LD (in the reviewed example, C = 2.5 m). The spectator's head is located at height of 1.6 m from the ground and the spectator's sight is directed to the LD at angle of about 45° to the horizon line. Therefore, the distance between the LD and the spectator's head L = 3.5 m (Fig. 1). It is worth noting that the possible range of LD view an-

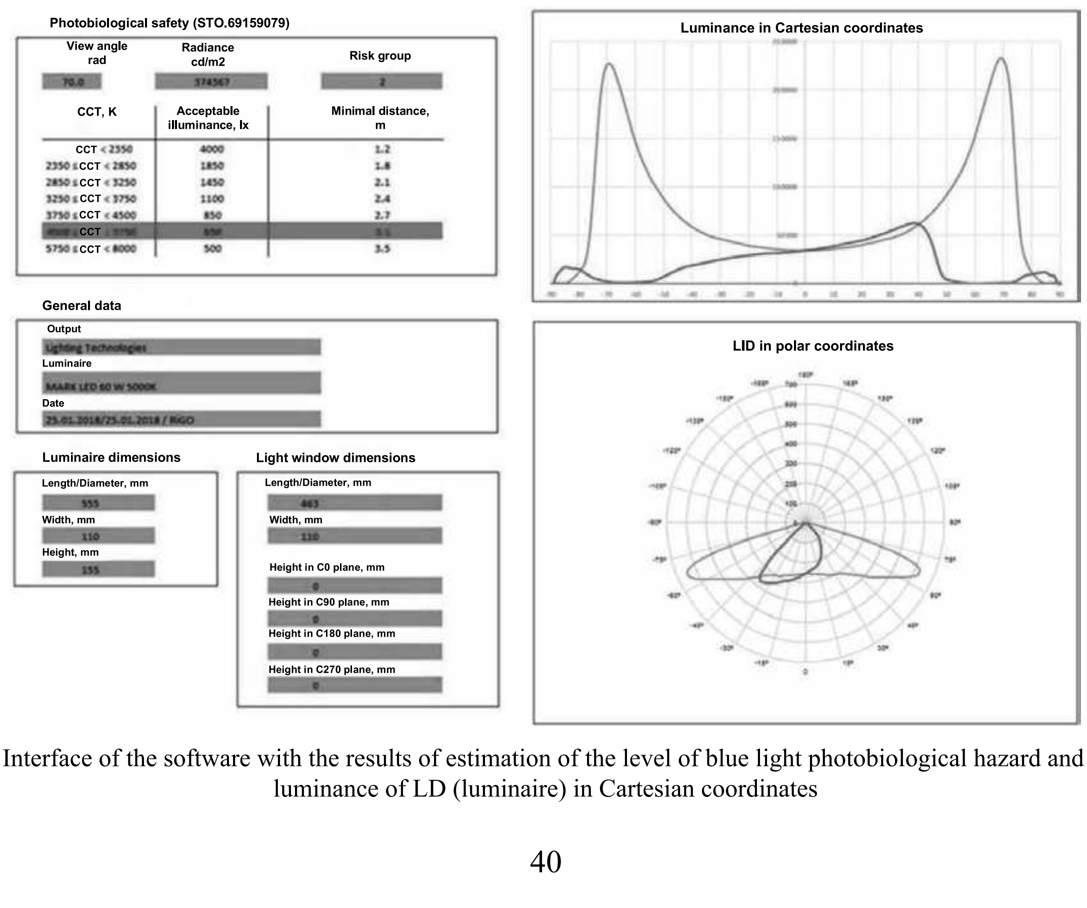


Fig. 3. Interface of the software with the results of estimation of the level of blue light photobiological hazard and overall luminance of LD (luminaire) in Cartesian coordinates

gles is (30÷60) ° and estimations of threshold distances for this type of LD may be made within this range.

At this distance, illuminance E_v on a virtual plane normal to the direction to LD is necessary to be measured. If luminous instensity in given direction I_v is known (e.g. using goniophotometer measurements), illuminance is defined as $E_v = I_v \cdot L^{-2}$.

Let's presume that the value of illuminance in the selected point is 750±75 lx. Then the condition of compliance with RG1 is met for the light source of LD with T_{cc} = 4000 K (Table 2) as 750±75 lx < 850 lx.

Therefore, 3.5 m is the distance at which the light source of LD can be seen without adverse consequences for visual apparatus. The minimal accepted threshold distance of the RG2 zone may be defined experimentally or by calculation more precisely.

After defining the value of threshold, it is necessary to place corresponding information in the technical documentation and a warning sign on RG2 classification in case of viewing from specific distance on the body of a general use LED-based LD.

Now let's presume that T_{cc} of the light source of LD is 5000 K. In this case, the RG1 compliance condition is not met. In accordance with IEC62778:2014, illuminance should not exceed 650 lx in this case. For defining of minimal accepted distance, it is necessary to place the virtual point of the spectator's head location at a higher distance in order to get the value of illuminance not exceeding 650 lx. In this case, the new value of this distance at which the light source of LD can be viewed without adverse consequences for visual apparatus (e.g. 4.5 m) will be defined. In this case, it will be necessary to place a warning sign indicating the minimal distance of 4.5 m on the body of the LED-based LD with RG2 radiation.

Classification of LD as RG0 is conducted using determination of overall luminance of the lighting body in the direction of spectator's eyes. Luminance is determined using a relevant measurement device in accordance with GOST R54350–2015. The position of the virtual spectator is selected on the basis of the above descripted example. If the measured (calculated) value of overall luminance is less than 10,000 cd/m^2, the LD is classified as RG0.

The described approach to estimation of RG of LD on the basis of photobiological safety allows us to use the data of spatial distribution of luminous intensity acquired by goniophotometer in the form of *LDT* files.

We have developed software allowing to estimate the said characteristics of LD. Apart from the luminous intensity distribution data, the *LDT* files contain information about electric and colour characteristics as well as dimensions of LD. Some parameters are input manually for calculation. First of all, it is the most probable angle of view of LD.

For convenience of the users, the information of LD luminous intensity and radiance distribution is output in the form of graphs (Figs. 2, 3). Such information is useful for analysis of the space around LD and determination of the most hazardous areas in terms of photobiology. Then the software checks all meridian planes at the above said angle and indicates the maximum one.

Comparison of the results acquired and the results of tests conducted in certified laboratories allowed to ascertain that the simplified method estimations in accordance with IEC/TR62778:2014 are estimations of hazard from above. This allows to determine the distance to safe areas of spectator position, i.e. the areas where the photobiological safety RG1 conditions for white light LD are met, and to place such information in a warning sign on the body of LD if necessary.

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Light & Engineering
Vol. 27, No. 5, pp. 43–54, 2019 *https://doi.org/10.33383/2019-063*

OPTIMISATION OF LIGHTING PARAMETERS OF IRRADIATION IN LIGHT CULTURE OF LETTUCE PLANTS USING LED EMITTERS

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ABSTRACT

The results of the ending phase of photo biological studies of capacity of lettuce and basil grown in conditions of a phytotron with irradiation by radiation of different ratio of fractions in the red-blue and blue-green-red regions of photosynthetic active radiation (PAR) are presented[1].

The spectral variants of PAR providing the maximum or near to maximum capacity of the specified cultures are found.

The complex and multiple-valued nature of effect of main PAR spectral regions on photo energetic and photo regulatory processes in plants providing their capacity is highlighted, which makes it impossible to determine common unified requirements to optimal parameters of artificial irradiation for growing of plants. These requirements shall be defined on the basis of direct photo biological experiments with main species of agricultural plants and be the most important element of the general photo culture macro technology.

The general principles of fulfilment of the specified requirements to PAR spectra of phytoemitters are reviewed, including with consideration of setting of normal vision conditions for personnel of greenhouses and other protected ground structures.

Keywords: photo biological studies, light (photo) culture, LED-based phytoemitter, photosynthetic active radiation (PAR), action spectrum, photosynthetic photon flux (*PPF*), photosynthetic photon irradiance or flux density (*PPFD*), photosynthetic photon efficacy (*EPPF*)

1. INTRODUCTION

Opportunities to obtain direct experimental data on the effect of radiation in particular regions of PAR on capacity of specific species of plants using light emitting diode (LED) emitters stimulate photo biological studies (FBS) throughout the world. The priority of the specified direction was confirmed during the *GreenSys* 2019 International Symposium on advanced technologies and management for innovative greenhouse which took place in June 16–20 in Angers (France).

Nowadays, the problems of application of LED in plant growing are becoming practical ones, in particular, due to rapid widening of application of *City Farm* installations for vertical multi-layer growing of lettuce and leaf vegetables.

Lettuce and leaf vegetables is the third largest group of vegetables grown in the Russian greenhouses (Fig. 1), and due to the fact that the country's demand for fresh and rich in vitamins greengrocery is satisfied for not more than (20–30)% during winter, the potential of production development in this area is high and scientific achievements are strongly sought-for.

The article [1] presents the results of the first phase of the FBS conducted by the authors using a phytotron in lettuce and basil photo culture

[1] See also article [1].

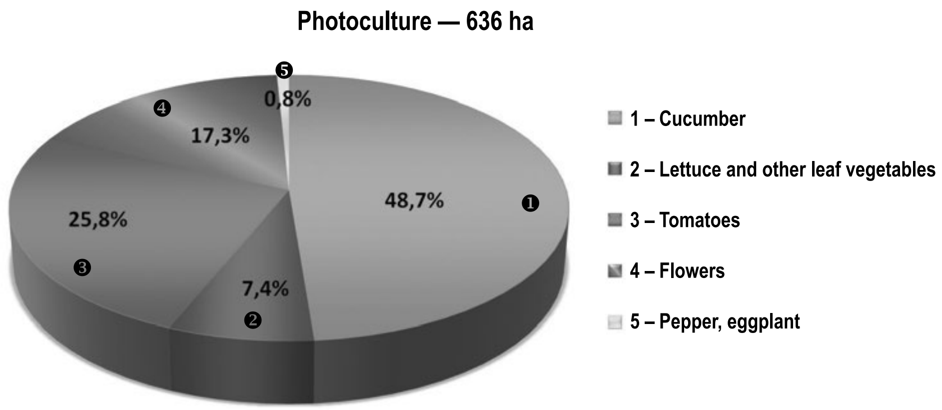


Fig. 1. Areas occupied by vegetable photo cultures in the Russian greenhouses in 2019

(at K.A. Timiryazev RGAU-MSKhA) using the developed special quasi-monochromatic LED-based phytoemitters (PE). For the first time, the data obtained in the wide range of varied lighting parameters (spectrum in the PAR region and irradiation level) allows us to start solving the problem of optimisation of PE spectral characteristics for industrial growing of the specified salad crops.

2. FBS METHOD AND THE EXPERIMENT INSTALLATION

As a result of the first phase of the FBS [1], the region of *PPFD* in interval of (160–180) µmol/(s·m²), corresponding to maximum capacity of Landau lettuce and Russian Giant basil, was established. Afterwards, all experiments with red-blue (*RB*) and red-green-blue (*RGB*) PE were conducted at *PPFD* equal to 170 µmol/(s·m²) ±10 %. That is allowing to reduce the number of expensive and rather long-term vegetation periods and complies with the provisions of the "surrogate optimisation" method used in contemporary biology in the course of research of the effects of external factors on plants [2–4].

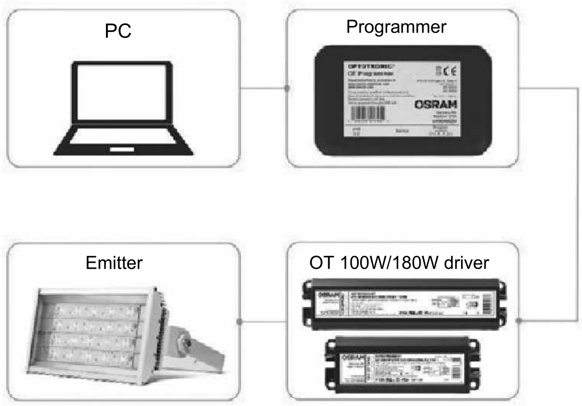


Fig. 2. Flow graph of regulation of LED-based phytoemitter parameters in the FBS

The goal of the second phase of the FBS, which was also conducted using the phytotron of K.A. Timiryazev RGAU-MSMKhA, was to study the effects of joint radiation in the main regions of PAR.

The experiment was designed in the following manner: first, the impact of the ratio of radiation levels in the red (*R*) and blue (*B*) regions (*RB*, "binary optimisation") was studied, then different fractions of the green region of PAR were added (*RGB*, "triad optimisation").

In accordance with this, by order of VNISI, two groups of PE devices, accordingly *RB* and *RGB*-types, with parallel switching on of LEDs of the said colours and function of independent control of currents and the *PPF* using two or three colour channels respectively, were manufactured by AO KETZ factory.

Like at the first phase of the FBS, high-output *R*, *G* and *B* LEDs manufactured by *CREE* were used (Table 1). By changing the current in each channel (previously, dependence between *PPF* and current had been determined), it was possible to vary the fraction of each region in the total irradiation from 0 to 100 %. For regulation of PE current, the controlling device (driver) *OT180W/UNV1250C* and *Optotronic OT programmer* manufactured by *OSRAM* were used (Fig. 2).

The measurements of PE radiation spectrum were made by means of the *PC100N* spectrometer by *UPRtek* (Taiwan) with software by Intekh-Lighting (Russia), the values of *PPFD* in each region and total irradiation were determined by means of the *PPFD* meter *Li-250A* with quantum detector *Li-190R* (*LI–COR*, USA).

Table 1. Main Parameters of the Colour (*R*, *G*, *B*) LEDs used in FBS

Item	LED type (manufacturer)	Peak wavelength, nm	Spectral region of radiation, nm (at 0.5 level)	Current adjustment range, mA
1	*XPEEPR-L1–0000–00901*, *XPE HE Photo Red Light Emitting Diode* (*CREE*)	656	645–666	350–800
2	*XPEBGR-L1–0000–00F01*, *XLamp XP-E Light Emitting Diode Green* (*CREE*)	517	500–540	500–1100
3	*XTEARY-00–0000–000000Q01*, *XLamp XT-E Light Emitting Diode Royal Blue* (*CREE*)	447	435–458	500–1200

Table 2. The Results of Binary Optimisation

Item	1	2	3	4	5	6	7	8
Spectrum type	*R*100 % *B*0 %	*R*90 % *B*10 %	*R*80 % *B*20 %	*R*0 % *B*40 %	*R*50 % *B*50 %	*R*40 % *B*60 %	*R*32 % *B*68 %	*R*0 % *B*100 %
Weight (lettuce), g	92.5 ± 13.2	71.5 ± 5.2	98.7 ± 10.5	56.7 ± 13.9	76.9 ± 7.6	59.0 ± 12.2	66.6 ± 14.8	69.3 ± 3.5
Weight (basil), g	25.8 ± 5.7	55.1 ± 12.3	65.9 ± 14.7	51.2 ± 6.9	58.2 ± 5.0	65.9 ± 5.7	30.5 ± 7.8	18.7 ± 8.5

The other conditions of the experiment complied with the requirements of the technology of growing of lettuce and leaf vegetables adopted for the specified phytotron are the next:

• The experiments were conducted with permanent 18h photoperiod at day and night air temperatures of 22 °C and 18 °C respectively. The plants were grown in vegetation vessels with Agrobalt S nutrient mixture, 3 (lettuce) or 5 (basil) plants in each vessel. The substrate was high-moor neutralised peat with low degree of decomposition, humidity not exceeding 65 %, and containing limestone (dolomitic) meal and a complex fertiliser (N_{total} – 150 mg/l, P_2O_5–150 mg/l, K_2O – 250 mg/l, *Mg* – 30 mg/l, *Ca* – 120 mg/l, microelements) with *pH* in range 5.5–6.6. Watering was conducted in accordance with weight, humidity was maintained at the level of 70 %, repeatability was equal to four times.

• Crop biomass accounting and other determinations were conducted 35 days after sprouting, total biomass per vessel was taken into account.

3. FBS RESULTS AND DISCUSSION

• Binary Optimisation

The spectra of the implemented eight *R-B* combinations and corresponding fractions of $PPFD_R$ and $PPFD_B$ in total irradiance $PPFD_{R+B}$ are presented in Fig. 3 and Table 2. The same figure and table contain the vegetation results achieved in these conditions: the capacity *N*.

It shall be noted that dependences of *N* and the *R* and *B* ratio of radiation fractions are significantly different for lettuce and basil (Fig. 4). By substituting the range of *N* values of lettuce in the functions of this ratio using linear approximation (Fig. 5), we can see that the role and impact of *R* region of PAR on synthesis of biomass are obviously particularly important. At the same time, with growth of *R* fraction of radiation *N* of lettuce increases as well as it decreases with growth of *B* fraction of radiation. Unlike lettuce, the dependence of *N* of basil on ratio of *R* and *B* fractions may be presented by a curve with maximum corresponding to *R* fraction of (50–80)% and *B* fraction of, correspondingly, (50–20)%. The common requirement for both cultures is the *B* fraction of radiation in the PAR region at the level of about 20 % (sufficient level).

• Triad Optimisation

Research of dependence of *N* of lettuce and basil on ratio of *R*, *G* and *B* fractions of radiation (Fig. 6) was the following and final phase of surrogate optimisation of spectrum for the specified cultures.

Table 3 and Fig. 7 show the data on the eight implemented vegetations with different ratios of the *R*, *G* and *B* fractions and corresponding results of *N* for lettuce and basil, and Fig. 8 presents a 3D visuali-

Table 3. The Results of Triad Optimisation

Item	1	2	3	4	5	6	7	8
Spectrum type	*R*77 % *G* 12 % *B*11 %	*R*75.2 % *G* 13.0 % *B*11.8 %	*R*62.4 % *G* 17.7 % *B*19.9 %	*R*49.0 % *G* 36.0 % *B*15.0 %	*R*43.6 % *G* 21.5 % *B*34.9 %	*R*30.0 % *G* 50.0 % *B*20.0 %	*R*27.0 % *G* 31.1 % *B*41.9 %	*R*17.2 % *G* 13.7 % *B*69.1 %
Weight (lettuce), g	78.9 ± 14.4	84.7 ± 14.8	72.8 ± 4.0	62.5 ± 3.8	67.5 ± 12.4	76.5 ± 14.8	68.6 ± 11.9	50.8 ± 6.4
Weight (basil), g	49.8 ± 8.6	45.9 ± 11.1	73.1 ± 8.1	54.7 ± 15.7	26.6 ± 4.8	54.7 ± 5.0	37.0 ± 6.4	43.7 ± 8.5

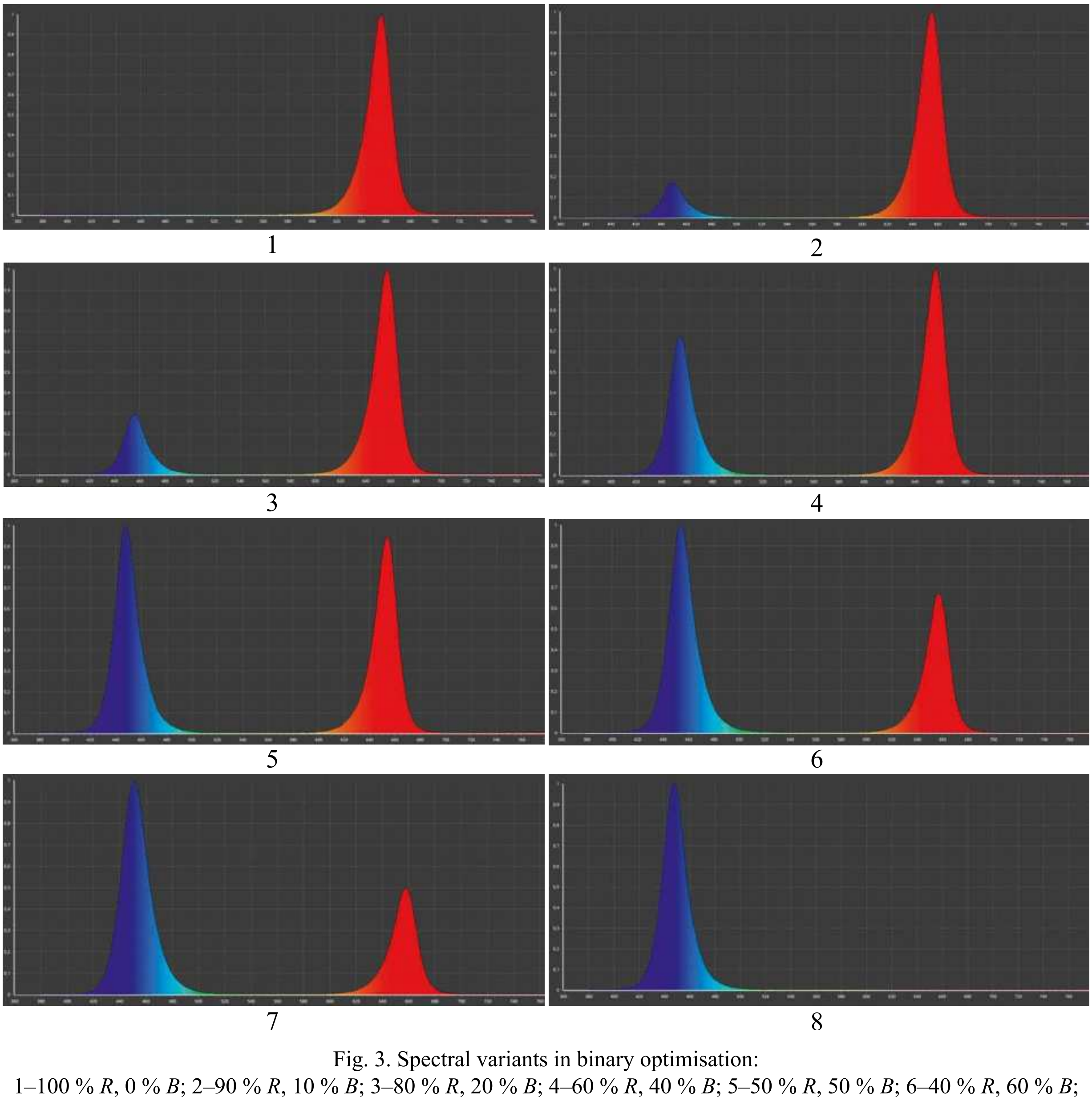

1 2 3 4 5 6 7 8

Fig. 3. Spectral variants in binary optimisation:
1–100 % *R*, 0 % *B*; 2–90 % *R*, 10 % *B*; 3–80 % *R*, 20 % *B*; 4–60 % *R*, 40 % *B*; 5–50 % *R*, 50 % *B*; 6–40 % *R*, 60 % *B*; 7–32 % *R*, 68 % *B*; 8–0 % *R*, 100 % *B*

sation of the dependence of capacity *N* (biomass, g) on *R* and *B* fractions of radiation (considering that $G = 100 - (R + B)$) compiled by means of *Wolfram Mathematica* using a 3D grid and linear interpolation. The colour of the surface of the graphic model corresponds to the real colour of spectrum in the given regions *R* and *B* along the axes of coordinates.

Clarity of the presented *3D* models allows us to state the following qualitative estimations of joint action of *R*, *G* and *B* fractions of PAR:

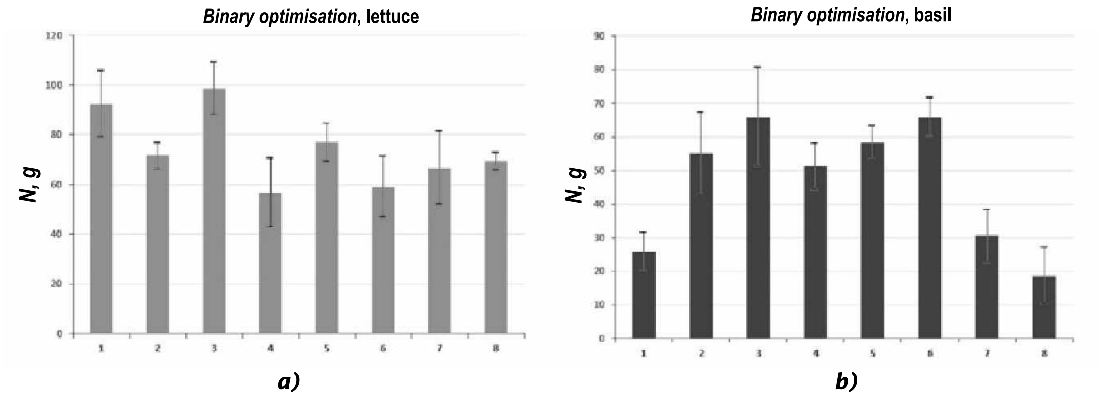


Fig. 4. Capacity diagrams of lettuce (*a*) and basil (*b*) with binary optimisation

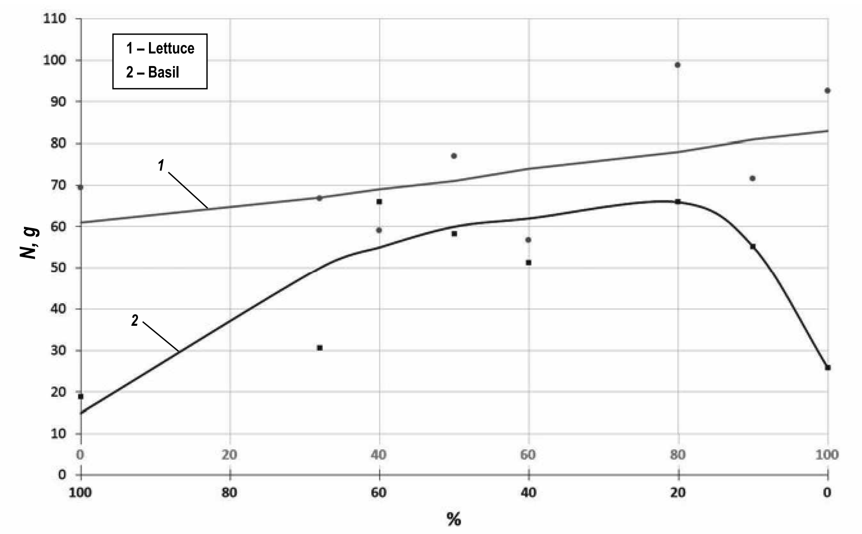


Fig. 5. Graphic interpretation of the results of binary optimisation

- In the region of maximum capacity of both cultures, priority of *R* (red) radiation is obvious, especially for lettuce;
- Prevailing fraction of *B* (blue) radiation leads to dramatic reduction of *N*. Tables 2,3 and Fig. 4, *a* and 7, *a* show that maximum values of *N* of lettuce were reached at fully *R* radiation ($R_{100\ \%}$) as well as at variants $R_{80\ \%}$: $B_{20\ \%}$ and $R_{75.2\ \%}$: $G_{13\ \%}$: $B_{11.8\ \%}$. Decrease of *N* down to 40 % and less corresponded with significant prevailing of *B* radiation. Availability of *G* (green) radiation in the PAR region is not mandatory but is acceptable.

The corresponding data on basil (Table 2,3 and Fig. 4, *b* and 7, *b*) confirms complex nature of joint effect of *RGB* radiation on this culture; the best results in terms of biomass weight (*N*) were reached in vegetation with a triad combination $R_{62.4\ \%}$: $G_{17.7\ \%}$: $B_{19.9\ \%}$ and the results with the nearest values of *N* were achieved for binary *R*-*B* combinations $R_{80\ \%}$: $B_{20\ \%}$ and $R_{40\ \%}$: $B_{60\ \%}$.

It shall be noted that, apparently, availability of even minimum fractions of *R* radiation in the polychromatic spectrum is absolutely necessary for basil. At the same time, with full *B* radiation, *N* was equal to just 25 % of the possible maximum. But irradiation of basil with only *R* radiation is also very unfavourable (about 35 % of the maximum value of *N*).

Fig. 9 presents the spectral combinations providing maximum or nearly maximum capacity for lettuce and basil. It is obvious that this data will be different in the photosynthetic photon and energy systems of quantities. The relation between the values of radiation fractions in the studied regions is defined using the expression $E_{PPFD} = K \cdot E_e$ [μmol/(s·m²)], where

E_e is the irradiance [W·m^{-2}],

$$K = (h \cdot c \cdot N_A)^{-1} \times$$
$$\times \int_{400}^{700} e(\lambda)\lambda d\lambda \,/ \int_{400}^{700} e(\lambda) d\lambda [\mu\text{mol} \cdot \text{J}^{-1}],$$

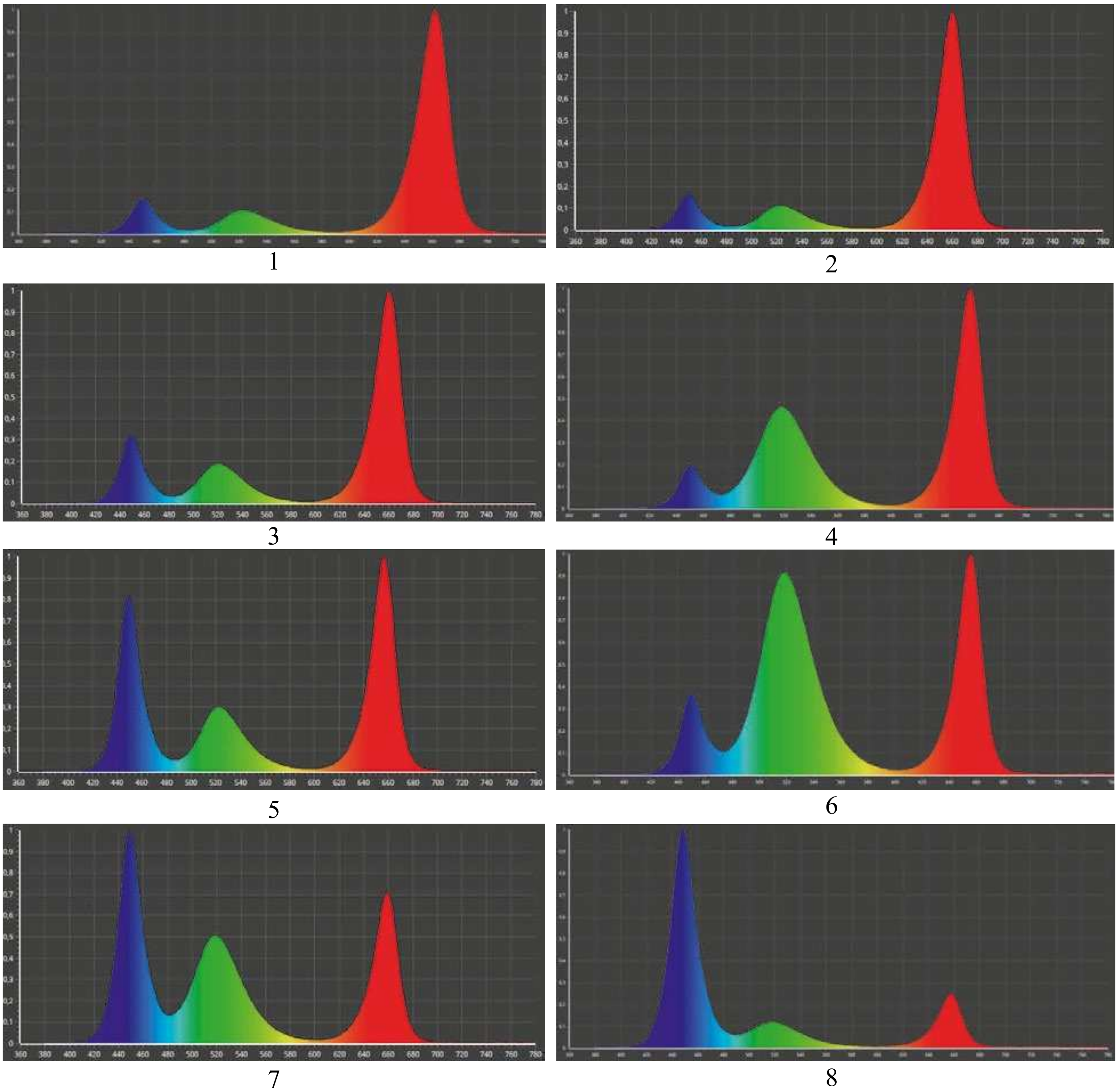


Fig. 6. Spectral variants in triad optimisation:
1–77 % *R*, 12 % *G*, 11 % *B*; 2–75.2 % *R*, 13 % *G*, 11.8 % *B*; 3–62.4 % *R*, 17.7 % *G*, 19.9 % *B*; 4–49 % *R*, 36 % *G*, 15.0 % *B*; 5–43.6 % *R*, 21.5 % *G*, 34.9 % *B*; 6–30 % *R*, 50 % *G*, 20 % *B*; 7–27 % *R*, 31.1 % *G*, 41.9 % *B*; 8–17.2 % *R*, 13.7 % G, 69.1 % *B*

where

$e(\lambda)$ is the spectral irradiance [$W \cdot m^{-2} \cdot nm^{-1}$],

λ is the radiation wavelength [nm],

h is the Planck constant [J·s],

c is the speed of light [m/s],

N_A is the Avogadro constant [μmol^{-1}].

We would also like to note a very practically important fact that, when using *RB* or *RGB*-type PAR spectra, at fraction of *R* radiation less than 75 % for lettuce and less than 50 % for basil, it is not possible to reach high value of *N* for these cultures.

Over the last year, there were a number of interesting studies containing the results of FBS on *N* of leaf vegetables with PAR spectrum variation. It is of interest to briefly compare their data with that presented in this article.

In one of the first of the serious works regarding application of LED-based PE devices, [5], it was noted that addition of *G* radiation to *RB* radiation (by means of green fluorescent lamps (FL) with rather wide spectrum) at *G* fraction of 24 % increased *N* of lettuce by about 1.5 times, whereas

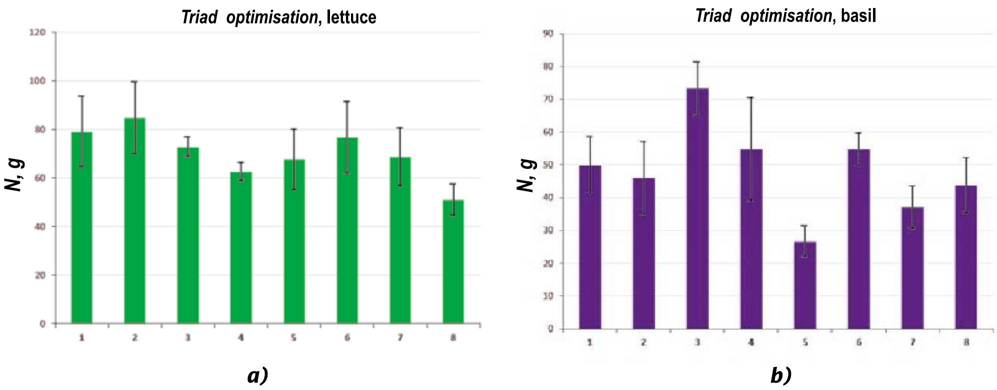


Fig. 7. Capacity diagrams of lettuce (*a*) and basil (*b*) with triad optimisation

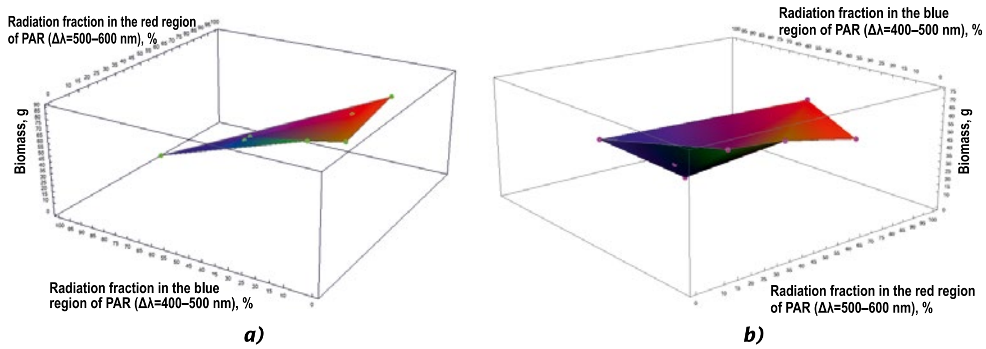


Fig. 8. *3D* models of capacity for lettuce (*a*) and basil (*b*) with triad optimisation

increase of this fraction up to 51 % negatively affected *N*.

The article [6] states that the data of many studies of *G* radiation affecting on *N* of leaf vegetables are very ambiguous and vary between "adverse" and "extremely useful".

In the work conducted by the specialists of Taiwan National University using a phytotron, the *Boston lettuce*-breed lettuce was grown in 35 days at *PPFD* of 210 μmol/(s· m²) with photoperiod of 16 h with irradiation by means of a LED-based PE with *RB* and *RWB* (addition of white, *W*) spectra as well as under cold white FL [7]. The maximum value of *N* corresponded to the *RWB* combination, the FL variant was 10 % lower and the result of the *RB* combination was 17 % less than the maximum one.

We would also like to mentioned a small-scale experiment conducted by *Samsung* in cooperation with the Seoul National University in South

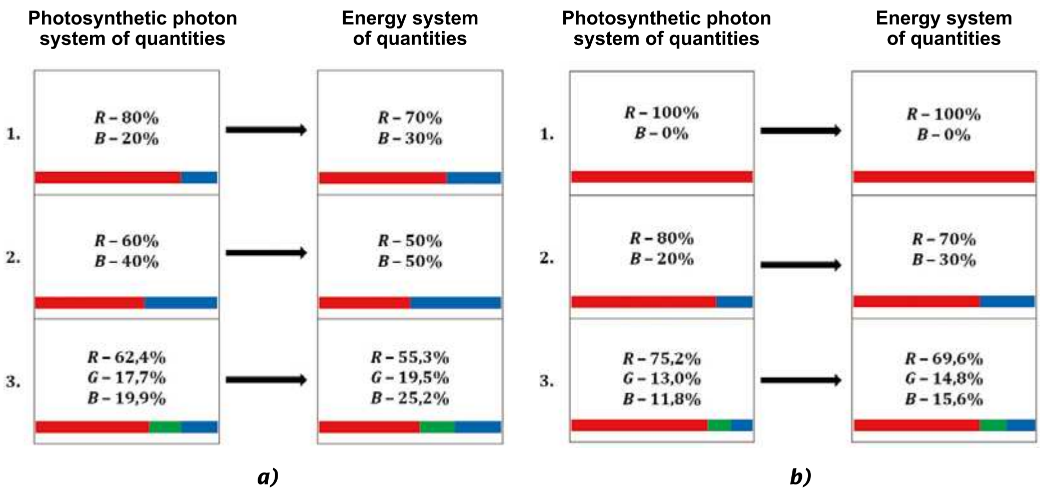
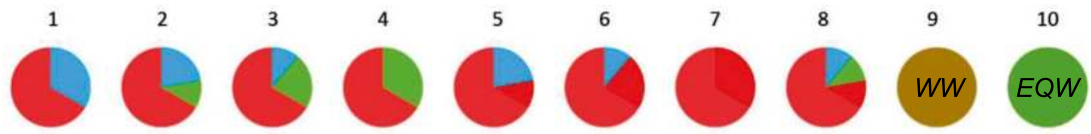


Fig. 9. The most favourable spectral characteristics in the PAR region for lettuce (*a*) and basil (*b*)



	1	2	3	4	5	6	7	8	9	10
FR	0,0%	0,0%	0,0%	0,0%	11,1%	22,2%	33,3%	11,1%	9,4%	3,3%
R	66,7%	66,7%	66,7%	66,7%	66,7%	66,7%	66,7%	66,7%	54,4%	27,8%
G	0,0%	11,1%	22,2%	33,3%	0,0%	0,0%	0,0%	11,1%	30,6%	60,6%
B	33,3%	22,2%	11,1%	0,0%	22,2%	11,1%	0,0%	11,1%	5,6%	8,3%

Fig. 10. Variants of the experiments in the work [10] with different spectral combinations of PAR and near-IR regions

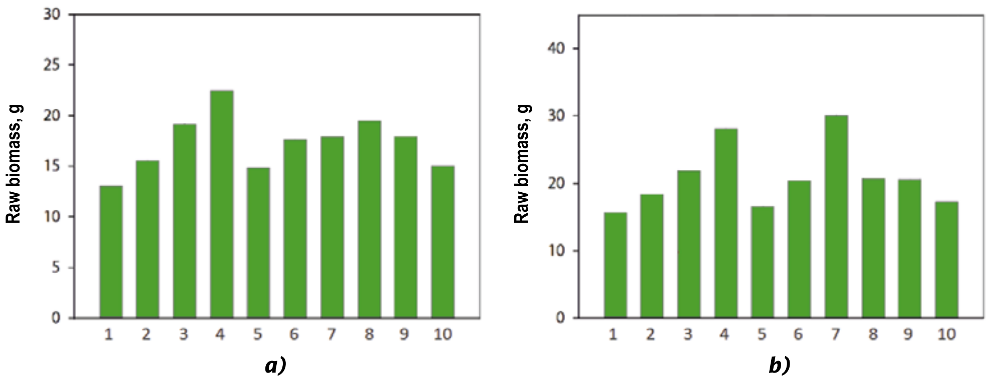


Fig. 11. Capacity diagrams of *Rex* (*a*) and *Rouxai* (*b*) breeds of lettuce with different spectral combinations of PAR and near-IR regions [10]

Korea [8–9]. Lettuce and basil were grown at *PPFD* equal to160 µmol/(s·m²), which is close to the one taken in our FBS using PEs with different spectrum variants: $R_{44.5}G_{44.5}B_{11}$; $R_{40}G_{40}B_{20}$; $R_{79}G_{14}B_7$, and $R_{80}B_{20}$. The best value of *N* for lettuce was with the first one (with equal fractions of *R* and *G* and the minimal *B* fraction), whereas the worst result (with capacity decreased by 56 %) was shown by the binary combination of $R_{80}B_{20}$. At the same time, the differences in efficiency of the specified variants for basil did not exceed 15 %.

The most serious study of radiation affecting with different spectra in the PAR region [10] also shows at ambiguity of the data of different authors on spectral efficiency of PAR in terms of yielding capacity. It mostly relates to the effect of *G* fraction of radiation. Negative effect of reduction of *R* and *B* ratio (*R*: *B*) in the PAR region on growth and development of vegetables is also noted. In their own FBS, using the original method, first, lettuce of two breeds, *Rex* and *Rouxai*, was grown in conditions of a phytotron for 10 days under white light with T_{cc} of 2700K (*FR*: *R*: *G*: *B* = 10.1 %: 54.5 %: 28.85 %: 6.5 %) with *PPFD* of 180 µmol/(s·m²)[2]. Then the plants were moved to the lighting installation (LI) with different spectral variants (Fig. 10). It shall be noted that the *R* fraction of radiation was constant in absolute terms: $PPFD_R$ of 120 µmol/(s·m²) which was equal to 66.7 % of the total radiation ($PPFD_{PAR}$ and $PPFD_{PAR+IR}$). In the last two variants, warm (*WW*) and cold (*EQW*) PEs with full (*FR-R-G-B*) spectrum were used.

The results of these FBS are presented in Fig. 11. Maximum value of *N* of *Rex* lettuce was reached in variants with *RG* (!) radiation (*R*: *G* = 66.7 %:33.3 %), whereas for *Rouxai* lettuce, the maximum was reached with *FR-R* radiation (*FR*: *R* = 33 %:66.7 %).

The increased efficiency of *G* radiation discovered by the author of the reviewed article allowed him to state an opinion that the effect of the *G* range of PAR region on *N* of lettuce is comparable with that for the *B* range and is approximately equal

[2] As we can see, apart from the effect of PAR, the effect of IR radiation in the spectral region of (760–800) nm (*FR* radiation) on *N* of lettuce was also assessed.

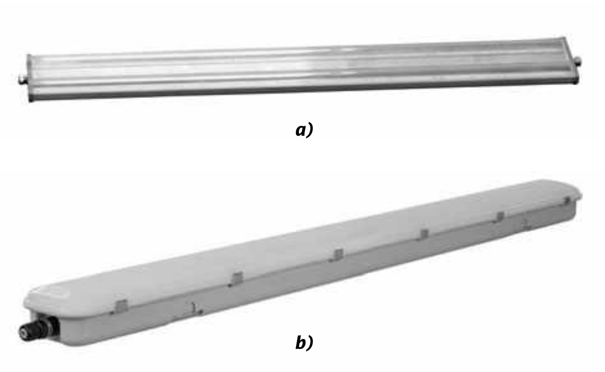


Fig. 12. *Top* emitter with *Galad Top Line Phyto LED*, power of 230W (a), and *Galad* LED-based emitter for multi-layer installations *Arcline Phyto LED*, power of 30W and 60W (*b*)

to 50 % of efficiency of *R* radiation. Also, in some cases, with significantly different spectral characteristics of PE, he achieved equal or close results of *N* for both breeds of lettuce.

Summing up the discussion of our own results and their comparison with the results of foreign studies of *N* of leaf vegetables, we would like to note the following:

- The results of our study and a rather large amount of data in the cited works allow to state that assessment of joint effect of different spectral ranges of PAR on *N* of plants, as exemplified by lettuce and leaf vegetables, is complicated by synergetic (superadditive) or, on the contrary, antagonistic effects of interaction which seem to be common for plants as complex receivers of radiation with large amount of photopigments. In other words, the term "optimal spectrum of radiation for growing of plants" is a rather abstract and ambiguous term. Even for one species of plants, requirements for the favourable spectrum providing the maximum value of *N* may vary notably.
- The complex nature of interaction between photo-energetic and photo-regulatory processes in plants may lead to achievement of the same or close effects (*N*) for regions of PAR and near IR radiation with significantly different spectra. The data of our FBS with lettuce and basil and the results of works by other researchers confirm it. Therefore, we may propose that the concept of **equifinality** formulated by the Austrian biologist L. von Bertalanffy is applicable to the effect of radiation on the plants. The effect of photo-equifinality as a property of such self-balancing system as a higher plant may obviously be a subject of further studies.

4. PRACTICAL IMPORTANCE OF THE RESULTS

In one of the main reports of the *GreenSys 2019* symposium [11], the increase of the scale of plant FBSs with application of LED-based equipment was embraced, however, it was noted that there is some gap between the scientific results and their practical application. We would like to note that, while planning this FBS [1], we stated that practical focus was its main goal. In other words, the requirements to spectral characteristics of PE for conventional *top* irradiation of lettuce and leaf vegetables in greenhouses and for their growing in *City Farm* multi-layer vertical phyto-installations shall be set with consideration of the results of this FBS of lettuce and basil.

The data we achieved on the basis of the direct experiments provide developers with irradiating devices with a certain freedom of choice allowing to define the spectral characteristics of the latter not only based on the condition of minimisation of *N* of plants but also with consideration of LED energy efficiency, cost parameters and, which is absolutely necessary, prevention of adverse effect of blue radiation on sight of maintenance personnel [12, 13]. In some cases, consumers may specify another requirement significant for phyto-installations: necessity of correct visual perception of greengrocery products (visual organoleptic) for assessment of their quality and appearance (colour or chromaffin cells of leaves, non-availability of spots, lesions by insect pests, etc.).

With consideration of these circumstances, the problem of selection between the variants of quasi-monochromatic *R*, binary *RB* or *RGB* spectra may be solved in favour of the latter both for lettuce and basil.

Based on the FBS practical requirements to spectral characteristics of the PE fulfilment shall be performed with consideration of the level of *EPPF* of the used LEDs. Table 4 contains the main parameters of colour LEDs based on the own data of the leading manufacturers (as of mid-2019).

EPPF of LEDs is very important and defines competitive advantages against phyto-HPSL with their *EPPF* equal to (1.8–2.1) µmol/J (its value for a HPSL luminaire is 1.55–1.8µmol/J).

The Table 4 shows that a PE with *EPPF* of quasi-monochromatic *R* LEDs may reach (3.3–3.4) µmol/J (with consideration of electric losses

Table 4. Main Parameters of Colour LEDs from Leading Manufacturers

Manufacturer (country)	Type	Calculated minimum *PPF*, µmol/s	Dominant wavelength, nm	Direct current, mA	Direct voltage, *V*	*EPPF*, µmol/J
CREE (USA)	XPEBPR-L1–0000–00D01 XP-E2 Photo Red	2.5	min 650 max 670	350	2.05	3.44
	XPGDRY-L1–0000–00601 XP-G3 Royal Blue	2.8	min 450 max 465	350	2.82	2.83
	XPEBGR-L1–0000–00F01 XLamp XP-E Light Emitting Diode Green	1.11	min 520 max 535	350	3.2	0.99
OSRAM Opto semi-conductors (Germany)	GH CSSRM3.24-V5V7–1 Oslon Square Hyper Red	5.27	min 646 max 666	700	2.1	3.52
	GD CSSPM1.14-UO OSLON SSL 120 Deep Blue	2.63	min 439 max 457	350	2.85	2.33
	GD CSSRM2.14-ARAT-24–1 Deep Blue	5.25	min 444 max 457	700	2.9	2.59
Lumileds (The Netherlands)	*LUXEON SunPlus 20 Line Royal Blue L1SP-RYL0002F00000*	2.25	min 445 max 455	350	2.5	2.3
	LUXEON SunPlus 35 Line Deep Red L1SP-DRD0002F00000	2.08	min 655 max 670	350	1.95	2.9
Samsung (Repubic of Korea)	LH351H Deep Red	2.32	min 650 max 670	350	2.1	3.12
	LH351H Blue	2.8	min 440 max 460	350	2.86	2.8
	LH351H Far Red	1.96	min 720 max 740	350	1.9	2.91
Prolight Opto Technol-ogy Corporation (Taiwan)	PK2N-3LDE-HSD-U Royal Blue	2.84	min 448 max 458	350	2.9	2.8
	PK2N-3LME-HSD-T Crimson	2.64	min 650 max 670	350	2.05	3.83
	PK2N-4LME-HSDL–X2 Crimson	5.78	min 650 max 670	700	2.15	3.92

in the controller and optical losses of about 12 %), whereas for PE with binary *RB* spectrum it may reach (3.0–3.1) μmol/J.

When designing PE with *RGB* spectrum, with consideration of currently low energy efficiency of green LEDs (*EPPF* < 1μmol/J), it is more necessary to provide the required spectral composition of PAR by means of a combination of a blue LED with phosphor and a red LED.

The specified approaches are implemented in the course of design of phytoemitters for *top* irradiation of leaf vegetables in conventional greenhouses as well as for growing of the same cultures in *City Farm* phyto-installations (Fig. 12) in cooperation with the specialists of the OAO KETZ manufacture. The structure of the emitters allows us to implement the above-mentioned spectral combinations with consideration of distinctions and a set of requirements of a specific project.

The expression of the phyto-installation LI efficacy criterion $EPPF_{IL} = PPFD_{aver} / P_1$, where $PPFD_{\text{aver}}$ is the average *PPFD* of cenosis, μmol/(s·m^2) and P_1 is the specific installed electric power, W/m^2 [14] implies that only with higher *EPPF* of PE at least 40 % reduction of power consumption as compared with HPSL may be reached.

CONCLUSION

The conducted FBS defined the requirements for favourable radiation spectra of LED-based PEs providing maximum capacity of lettuce and basil. The difference between these requirements shows inevitability of application of an experimental approach to solving of such problems.

Due to the fact that the physical principles of LED-based equipment allowing to fulfil the favourable spectrum requirements discovered by this FBS but also, which is not least important, the irradiation level requirements [1], it can be said that there is an opportunity to create a light engineering technology (as the most important element of the macro-technology of a specific plant photo culture) with computer-controlled industrial growing of plants (*cyber-agriculture*).

ACKNOWLEDGMENTS

The study was conducted with financial support of the Ministry of Science and Higher Education as part of the "Comprehensive Studies in the Area of Plant Photoculture and Designing of Highly Efficient LED Phytoemitters Providing Increase of Energy Efficiency of Industrial Greenhouses" project. Grant Provision Agreement No. 14.576.21.0099 dated on 26.09.2017. Agreement ID: 0000000007417PD20002. Unique ID of the work (project): RFMEFI57617X0099.

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Light & Engineering
Vol. 27, No. 5, pp. 55–62, 2019 *https://doi.org/10.33383/2018-078*

METHOD OF VEGETATION DETECTION USING RGB IMAGES MADE BY UNMANNED AERIAL VEHICLES ON THE BASIS OF COLOUR AND TEXTURE ANALYSIS

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ABSTRACT

The article describes the capability of application of *RGB*[1] images made by digital cameras for detection of Earth surface (vegetation) types. A set of measures necessary to be taken for processing of the images made by unmanned aerial vehicles (UAV) in real-time is described. Application of analogue of vegetation index allows detecting vegetation on an *RGB* image, which increases the probability of correct detection of surface (vegetation) type. Methods of preliminary and thematic processing of images required for positive detection of surface types are considered. Texture analysis is applied for detection of vegetation type. The results of the processing of real images are provided.

Keywords: images, unmanned aerial vehicles, image processing, texture analysis, surface types

1. INTRODUCTION

Detection of types of Earth surface is an important problem for research and practice. One of the variants of solving this problem is the application of multispectral and hyperspectral data of Earth remote sensing [1, 2]. The data may be acquired using space and plane systems. The main developed methods include processing of surface images acquired in open spectral channels located in different regions of the spectrum. Preliminary knowledge of reflection spectra of Earth surface allows building methods of segmentation of Earth surface areas, therefore, to automatically categorise them. However, there is a specific aspect of such surveys related to the significant effect of the following confounders on measurements: measurement instrument, the illuminance of Earth surface, and atmosphere condition. All these factors cause imprecision of spectral properties of surveyed objects (surface types), therefore, they make it less probable to distinguish one object from another.

Application of data of spectral measurements conducted by unmanned aerial vehicles (UAV) allows increasing efficiency of detection and recognition of an object. This type of measurements is used for solving practical problems of agriculture, geology, geophysics, and Ministry of Emergency Situations [3]. For these purposes, many methods based on analysis of data acquired in specially selected combinations of spectral channels in different spectrum regions were developed. Complexity of processing of multispectral and hyperspectral [4] data is related to consideration of aspects of the process of measurement and the volume of acquired data. The acquired multidimensional image contains spatial and spectral information, where every pixel contains the vector of the spectral behaviour of a surface area consisting of subareas of different types. Before processing such data, it is necessary to take the distinctions of solar radiation transport through the atmosphere in the territory occupied (displayed) by this pixel. Variability of the acquired spectra for a particular pixel is high and depends on season and atmosphere condition.

[1] Digital model of an image

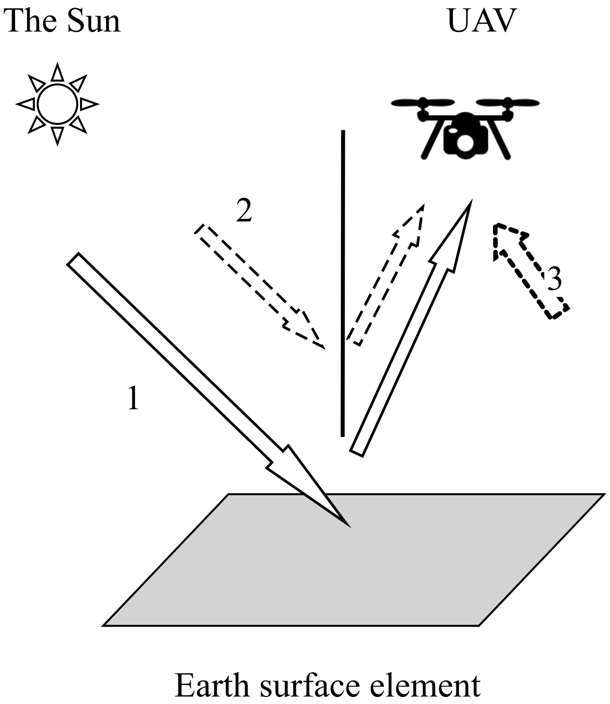


Fig. 1. Solar radiation fluxes received by optical receiver on board an UAV: 1 – radiation reflected from the surveyed area; 2 – radiation scattered in the atmosphere; 3 – diffused radiation

Digital images acquired by UAV are seldom applied for detection and recognition. This article considers the approach based on the combination of texture and colour analyses [5, 6] of acquired images for detection of vegetation on the images and recognition of its different types.

2. PROBLEM FORMULATION

A digital camera allows acquiring (measuring) images, which are possible to be processed by means of computer vision methods [7]. Then the acquired information, which most often constitutes an *RGB* image or multispectral data, is processed by means of relevant algorithms. The information on a *2D* image is a fixed radiation reflected from objects of the *3D* world. The quality of the image is determined by technical specifications of a measurement instrument (digital camera), the intensity of reflected radiation (zenith angle of the Sun and solar azimuth), type, the distance of the reflecting object, and the background (scene) [8]. Methods of computer vision allow extracting a large amount of information (colour, dimensions, form, etc.) out of the images. In the area of processing of the results of measurements acquired by means of UAV, the methods of computer vision are related to extraction of information out of the acquired data and its analysis.

A digital *RGB* image may be considered as two two-dimensional matrices with each matrix position corresponding to one pixel. For 8-bit images, the value of the magnitude measured in each pixel varies within the range of [0–255]. When designing processing methods, it is necessary to take into account that the image contains information, which is mainly determined by direct solar radiation and solar radiation reflected from different surface types. In the course of operation with images acquired by means of optic meters, it is necessary to take their radiometric characteristics, survey parameters, and atmosphere condition into account. In Fig. 1, a simplified scheme of information recording, which depends on the time of the day by an optic meter installed on the board of a UAV at a particular altitude above the Earth surface, is shown.

As it is shown in the figure, the radiation incident on the receiver is determined by reflected, scattered, and diffuse solar radiant fluxes. The solar radiation is partially absorbed by gases or scattered in the atmosphere, its part is absorbed and reflected by different types of surface. The measured data cannot be directly compared with reflection of particular surface types since there are many factors the radiation incident on the receiver depends on, such as receiver characteristics, settings of the digital camera, altitude and angle of surveying, survey conditions (solar azimuth and angle), atmosphere conditions (gas and aerosol composition of atmosphere), reflectivity of a surface. Therefore, before processing of the acquired images transforming contained data into surface reflectivity, it is necessary to conduct geometric and radiometric calibration [9].

3. CALIBRATION OF THE IMAGES MEASURED BY UAV

Combined geometric and radiometric calibration is especially necessary for comparison of data sets collected within several time periods. Naturally, receivers of the same territory register different data determined by illumination and survey conditions in different time periods. One of the differences regularly occurring in the course of real-time measurements is the change of flight altitude and angle of view, which depends on speed and direction of the wind. As digital cameras have a wide angle of view, the same area of the surface will be measured at different angles, whereas differences in time of the day when measurements are conducted and atmosphere conditions determined changes of illuminance (Fig. 2). It is especially necessary when a surface has a certain slope, which leads to changes of a measured magnitude, which depends on the angle of slope of the measured surface. Changes of UAV position depending on wind direction lead to changes of an image orientation in relation to the one acquired earlier (Fig. 2).

The radiometric correction allows correcting all measured values of radiation to the same conditions, i.e. to take the values of solar zenith and azimuth topography and illuminance (day of a year) values into account [9, 10]. Effect of the atmosphere is conditioned by aerosol scattering and absorption by gases. Usually, at a low latitude of UAV flight (100 m and less), atmospheric correction is practically not required. However, in some cases when the optical thickness of aerosol or mist may reach sufficient values, an atmospheric correction may be used [11]. Since most natural objects have anisotropic reflection characteristics, topographic effect correction is required [12].

Solar illumination geometry and terrain correction of a measured image *Im* may be presented by an expression:

$$I(i,j) = \frac{Im(i,j)\cdot\cos(Z)}{\cos(Z)\cdot\cos(S(i,j)) + \sin(Z)\times \sin(S(i,j))\cdot\cos(Az - As(i,j))}, \quad (1)$$

where $I(i,j)$ is the corrected image, (i,j) are indexes of the current pixel of an image, Z is the zenith angle of the Sun, S is the surface angle of slope, Az is the solar azimuth, As is the azimuth of a surface related to Northern direction. The terrain parameters (As and S) may be calculated using formulas given in [13, 14].

Geometric correction of acquired images conditioned by the deviation of flight trajectory from the set one caused by the wind may be conducted using the methods described in [15, 16].

Another aspect requiring attention for each image acquired in the course of the UAV flight above the surveyed territory is a colour correction. For this purpose, we propose to use the "grey world" method [17], when it is presumed that the sum of all colours of an image gives grey colour. By calculating the average values of chromaticity in each channel, it is possible to conduct the scaling of all subsequent images as compared to the first one. This will lead to equalising of chromaticity of all measured images.

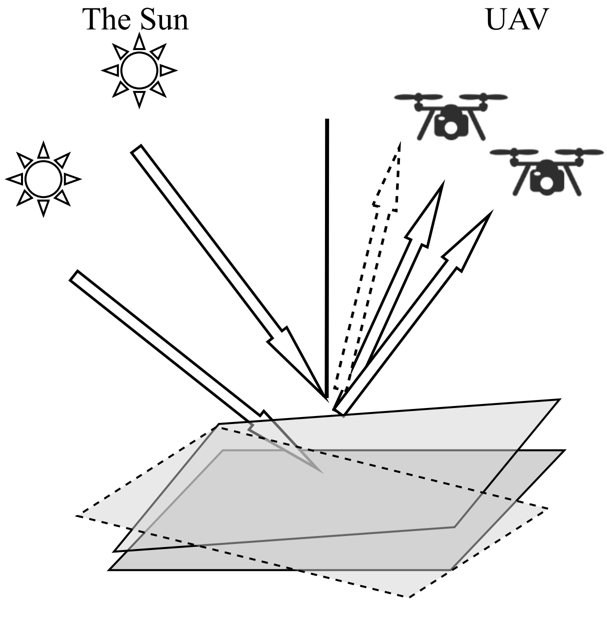


Fig. 2. Effect of measurement conditions and surface slope angle on solar radiant fluxes received by optical receiver on board an UAV

Average chromaticity for *RGB* channels may be calculated using the following formulas:

$$\langle R\rangle = \sum\sum\frac{R(i,j)}{N\cdot M};\langle G\rangle = \sum\sum\frac{G(i,j)}{N\cdot M}; \quad \langle B\rangle = \sum\sum\frac{B(i,j)}{N\cdot M}, \quad (2)$$

where R, G and B are the values of chromaticity for R, G and B channels respectively, N and M are the horizontal and vertical numbers of pixels respectively.

The value of grey colour may be calculated using the following formula:

$$Grey = \frac{w1\langle R\rangle + w2\langle G\rangle + w3\langle B\rangle}{3}, \quad (3)$$

where $w1$, $w2$, and $w3$ are empirical coefficients (e.g. $w1 = 0.213$, $w2 = 0.715$, $w3 = 0.072$ for chromaticity analysis, $w1 = 0.299$, $w2 = 0.587$, $w3 = 0.114$ for illuminance analysis).

Then chromaticity transformation for each channel will be conducted using the following formulas:

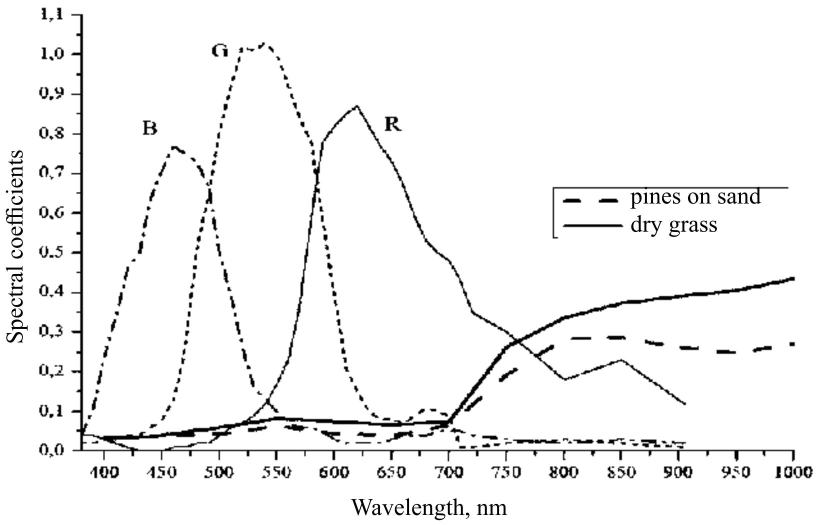


Fig. 3. Spectral response in *RGB* channels of *Canon* digital camera and spectral reflectance of vegetation

$$Rn(i,j) = \frac{R(i,j)\cdot Grey}{\langle R\rangle},$$
$$Gn(i,j) = \frac{G(i,j)\cdot Grey}{\langle G\rangle}, \quad (4)$$
$$Bn(i,j) = \frac{B(i,j)\cdot Grey}{\langle B\rangle},$$

where *Rn*, *Gn*, and *Bn* are the new values in the *R*, *G*, and *B* channels of an image respectively.

3. VEGETATION INDEXES

After preparation of the measured images, different problems of thematic processing may be solved. At the first step of processing, it is necessary to solve the problem of vegetation accentuation against the background (soil, buildings, etc.). One of the methods is related to calculation of *Colour Vegetation Index* [18], which unites radiation of two or more spectral bands reflected from the surface, which are related to *RGB* spectral coefficients of the digital camera and vegetation characteristics (Fig. 3). For calculation of vegetation characteristics from outer space, a popular one is *NDVI* (*Normalised Difference Vegetation Index*) [19] as it is calculated on the basis of green (500 nm) and near-infrared (800 nm) channels. Calculation of the difference between radiations with two values of wavelength allows to accentuate vegetation on a satellite photo. A typical digital camera installed on UAV is not equipped with a near infrared-channel, whereas the red channel includes the maximum of spectral reflectance of vegetation only partially (Fig. 3).

Nevertheless, the vegetation index *NDVI* may be calculated on the basis of the digital camera data:

$$NDVI = \frac{G-R}{G+R}\,. \quad (5)$$

Visible Vegetation Index (*VVI*) is a criterion of vegetation quantity in accordance with the following formula [20]:

$$VVI = \left[\left(1-\left|\frac{R-R_0}{R+R_0}\right|\right)\cdot\left(1-\left|\frac{G-G_0}{G+G_0}\right|\right)\times \times\left(1-\left|\frac{B-B_0}{B+B_0}\right|\right)\right]^{\frac{1}{w}}, \quad (6)$$

where *R, G, B* are the red, green, and blue channels of the image respectively; *Ro, Go, Bo* are the reference values of *R, G, B* channels for a particular colour scheme [21]; *w* is the weight index (the most frequently taken equal to 1).

In addition, such index as *Excess Green Index* (*ExG*) may be calculated:

$$ExG = 2G - R - B\,. \quad (7)$$

One of the popular vegetation indexes for the accentuation of vegetation on an *RGB* image is *CC* index (*canopy cover*):

$$CC = (1+L)\times\left((G-R)\times(G+R+L)\right), \quad (8)$$

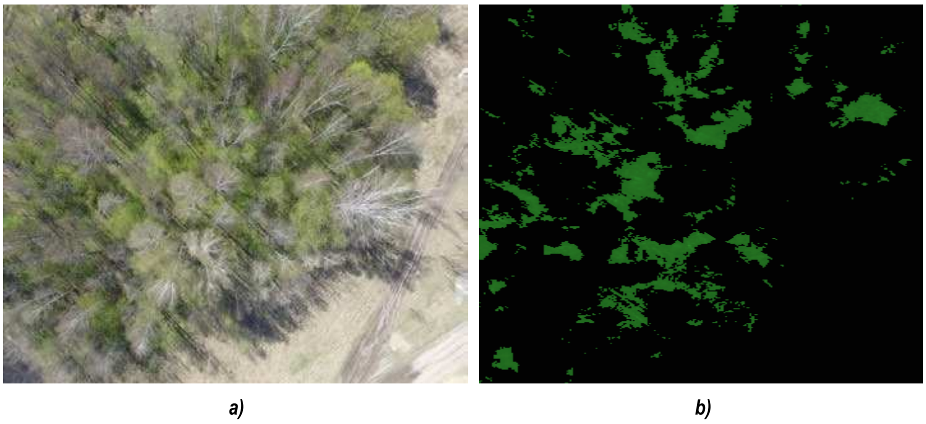


Fig. 4. Accentuation of vegetation on an image made by UAV: a – original RGB image, b – two-colour vegetation mask

where L is the soil factor equal to $L = 0$ for clean vegetation and $L = 1$ for clean soil (typically taken $L = 0.5$).

The indexes (5–8) allow accentuating areas occupied by vegetation on an image. Fig. 4 shows the result of accentuation of vegetation on an image acquired by UAV at an altitude of 15 m using filters based on the formulas (7) and (8).

4. METHOD OF VEGETATION RECOGNITION USING TEXTURE ANALYSIS

After an image acquired by means of UAV was corrected and vegetation was accentuated on it (Fig. 4b), it is possible to use the texture analysis method to determine the type of vegetation. For recognition of the vegetation type, it is necessary to process an image with a known plant and to get a template (containing only a plant without any background). Then, after conducting comparative colour and texture analysis of a new image and the template, the type of vegetation may be determined. The accentuated plant has a particular form with its area and contour possible to be measured.

For solving this problem, it is necessary to present the image in the form of shades of grey using the following expression:

$$Ig = 0.299B + 0.587G + 0.114R. \tag{9}$$

For the grey image, texture attributes are found:

– Root mean square:

$$P1 = \sum\sum \frac{\left(In(i,j)\right)^2}{N \cdot M}, \tag{10}$$

where $In(i,j) = \dfrac{Ig(i,j)}{\sum\sum Ig(i,j)}$;

– Correlation rate:

$$P2 = \sum\sum \frac{\left(In(i,j) - P1\right)}{In(i,j)}; \tag{11}$$

– Contrast (presents variations of chromaticity in different areas of the image):

$$P3 = \sum\sum (i-j)^2\, Ig(i,j); \tag{12}$$

– Discrepancy:

$$P4 = \sum\sum |i-j|\, Ig(i,j); \tag{13}$$

– Homogeny (relatively low values of this parameter witness low difference between data):

$$P5 = \sum\sum \frac{Ig(i,j)}{\left(1-(i-j)^2\right)}, \text{ or} \tag{14}$$

$$P9 = \sum\sum \frac{Ig(i,j)}{\left(1-|i-j|\right)}; \tag{15}$$

– Entropy (value of irreversible energy dissipation):

$$P6 = \sum\sum Ig(i,j) \cdot \lg\left(Ig(i,j)\right); \tag{16}$$

– Maximum (maximum value of pixel intensity (i,j):

$$P7 = max\left(Ig(i,j)\right); \tag{17}$$

Fig. 5. Cabbage image template

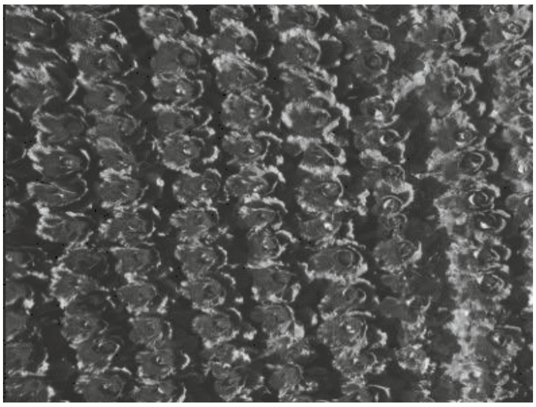
– Energy (characterises length and curvedness of contour):

$$P8 = \sum\sum Ig(i, j)^2. \quad (18)$$

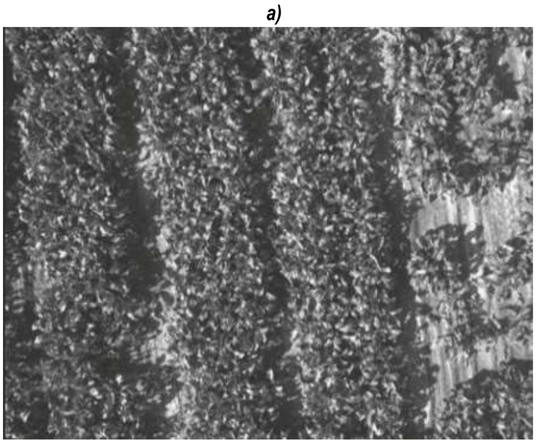
Then, after calculating texture attributes for the template of the required object and randomly taken areas of the image using formulas (10)–(18), the area may be categorised as an object by means of comparison. Comparison is made by calculating an approximation of the values of texture attributes with consideration of an operator:

$$C = \sum \frac{Ps(i) - P(i)}{Ps(i)}, \quad (19)$$

where *Ps*, *P* are the texture attributes for the template and the area of the image.



a)



b)

Fig. 6. Test images of field areas with: a – cabbage, b – beet crops

5. RESULTS OF NUMERICAL EXPERIMENTS

As an example of the method proposed by us, the results of surveying of a field with cabbage and beet crops were taken. In Fig. 5, the template of cabbage image is shown, using it, all the described corrections were conducted and texture coefficients were calculated, the results are listed in Table 1.

Fig. 6 shows test images of the field areas with cabbage (6a) and beet (6b) crops.

Then the images were processed in order to divide them into blocks containing separate homogeneous areas for which, using formulas (10)–(18), texture attributes *P1–P9* were calculated and compared with the template attributes using formula (19). As a result, the average percentage of correct guessing for the image 6a with the criterion C > 0.9 was equal to 88 %, and after comparing the template with image 6b, it was equal to 5 %. Part of the images with open soil was not recognised.

6. CONCLUSION

Technologies of monitoring by means of unmanned aerial vehicles are gradually being introduced into many spheres of research and practice. Technological problems of UAV development, routing, and measurements have already been transferred to ordinary routine mode. However, there is still a lack of processing software and especially software for analysis of the information acquired by means of UAV, and only some problems are solved. One of the problems, which is the most often solved by means of multispectral and hyperspectral equipment, is the classification of surface types. Such type of measurements allows solving problems of classification with high precision but is rather expensive and demanding in terms of measurement

Table 1. Texture Coefficients for the Cabbage Image Template (Fig. 5)

Texture coefficient	Average value	Dispersion
P1	$2.592 \cdot 10^{-5}$	$6.528 \cdot 10^{-7}$
P2	$2.782 \cdot 10^{4}$	$9.342 \cdot 10^{2}$
P3	$2.857 \cdot 10^{5}$	$5.191 \cdot 10^{3}$
P4	$1.419 \cdot 10^{2}$	1.262
P5	$8.883 \cdot 10^{-4}$	$6.945 \cdot 10^{-5}$
P6	6.322	$7.962 \cdot 10^{-2}$
P7	$1.811 \cdot 10^{-3}$	$1.449 \cdot 10^{-4}$
P8	$2.101 \cdot 10^{-3}$	$1.521 \cdot 10^{-4}$
P9	$5.057 \cdot 10^{-2}$	$1.320 \cdot 10^{-3}$

conditions. A simpler method proposed in this article is based on the application of a simple *RGB* digital camera. As atmospheric conditions of acquiring digital images constantly change, for equalisation of conditions of all images, geometric and radiometric correction is used. For recognition of surface types (several types of vegetation are considered in the article), we use textural analysis. The results given in the work confirm high precision of recognition of vegetation types on the basis of *RGB* images acquired by means of UAV. It should be noted that the texture analysis algorithm applied in this work is a rather simple one, and if it is used in more complex modifications, it should allow more precision type recognition for acquiring essential values of surface (vegetation in particular).

ACKNOWLEDGEMENT

The study was conducted as part of the national order of the Ministry of Education and Science of the Russian Federation, Project No. 8.8184.2017/8.9 "Methodology of Development of Energy-Generating and Energy-Transforming Systems for Onshore and Onboard Units of Onshore, Space and Underwater Facilities" and a youth project under the UMNIK programme.

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Fig.7. SKY LUM ceiling lights providing low glare and minimalistic design

Fig.8. SKY LUM pendant luminaires provide low light gradient from the ceiling and the light surface, producing low glare and the right light angles for NIF processes

Fig. Narboni, Godoy: a – São Paulo city centre, with illusive rivers; b – Valle de Anhagabau, final visualisation

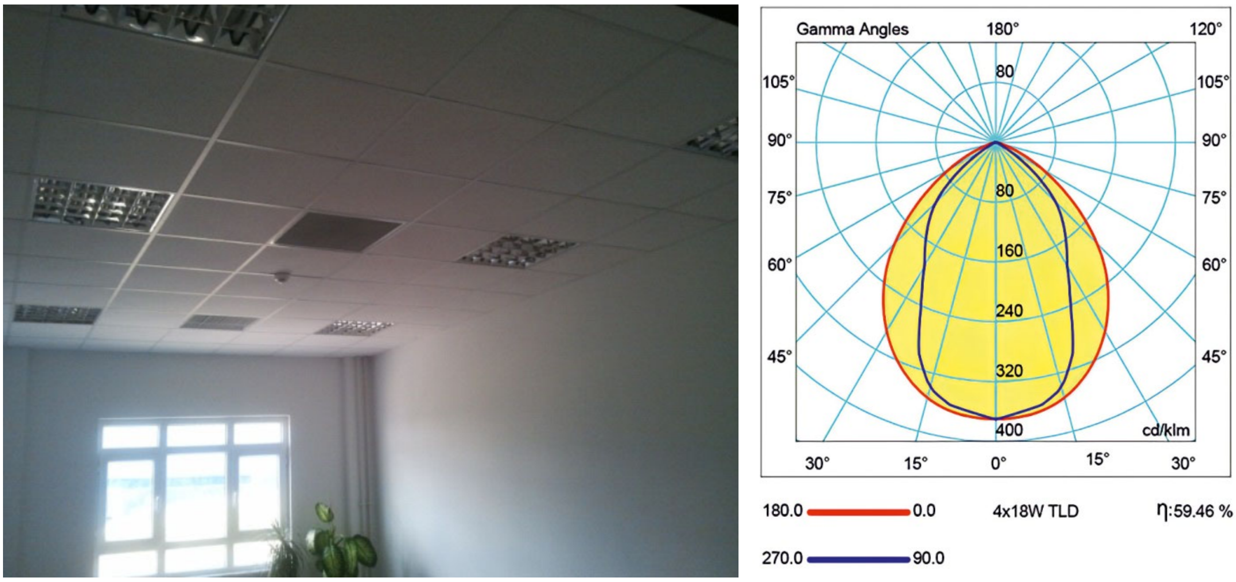

Fig. 2. Lighting system and light distribution curve of luminaires in Test Rooms 1, 2

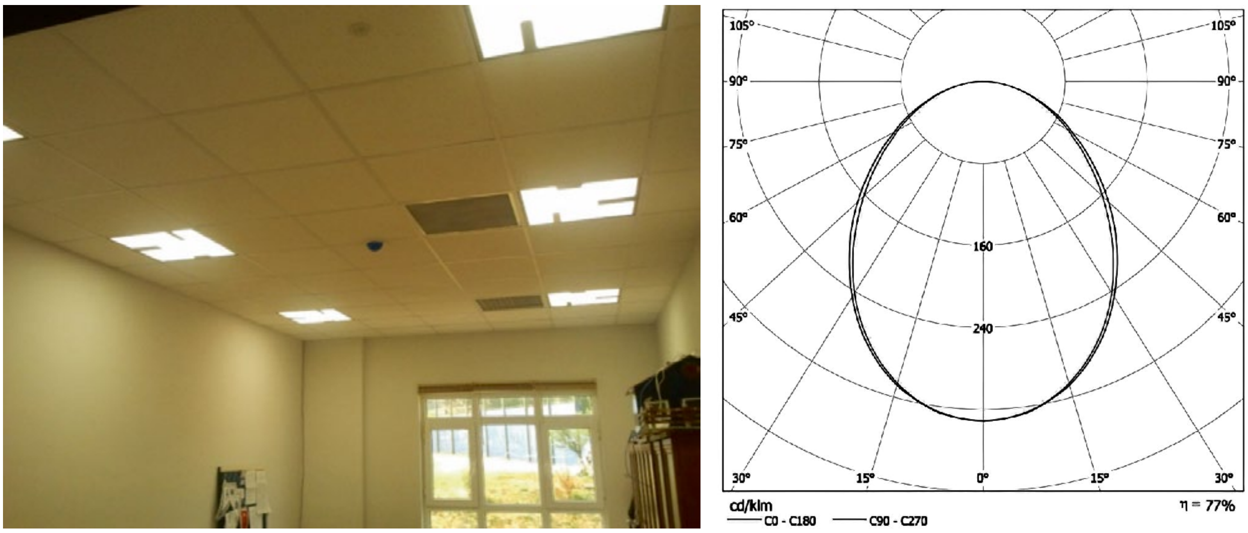

Fig. 3. Lighting system and light distribution curve of luminaires in Test Room 3

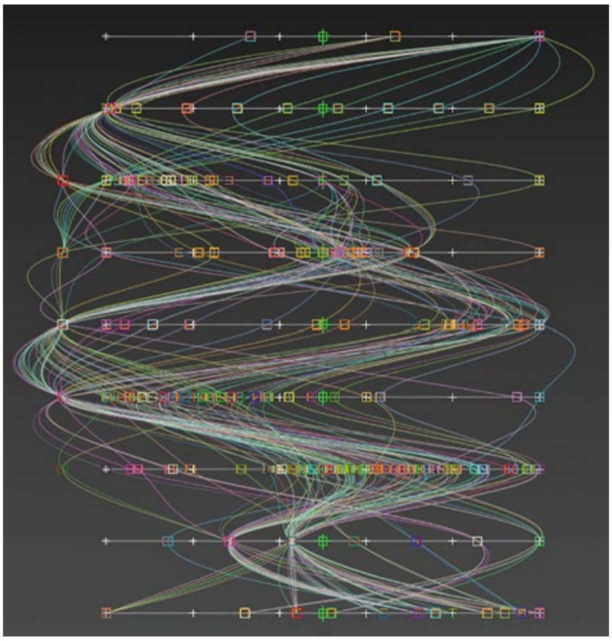

Fig. 1. The diagram of multivariate data that describes properties of Al/SiC MMCs (TCF and TLEF) depending on the method of composite forming, the volume ratio and the average size of SiC particles (year of the result included)

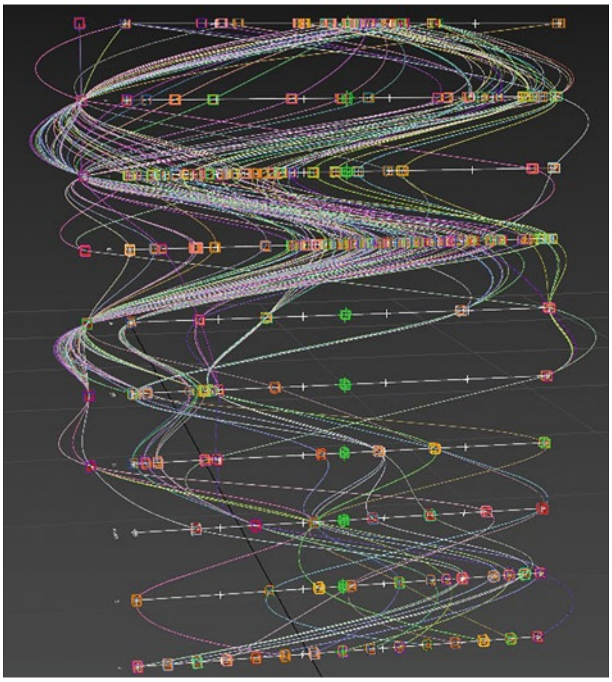

Fig. 2. The diagram of multivariate data that links the conditions and the methods of forming volume AL/SiC MMCs with some basic properties of the materials (TCF and TLEF)

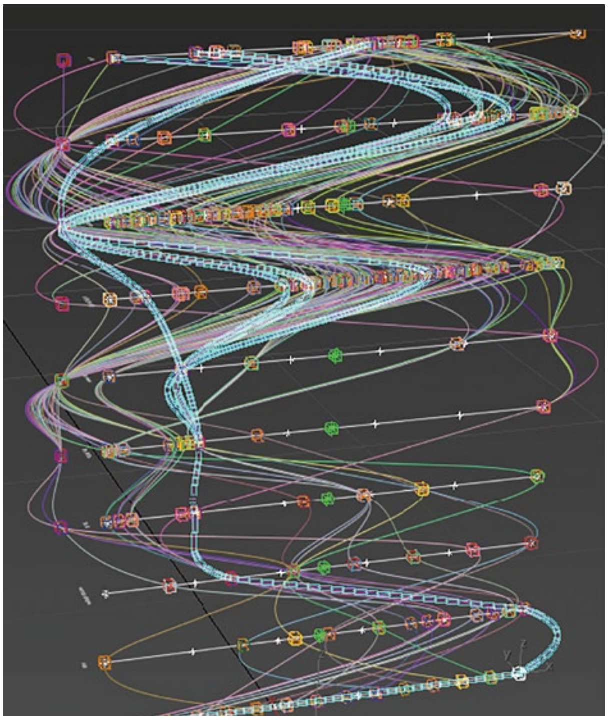

Fig. 3. The diagram of multivariate data that links the conditions and the methods of forming volume AL/SiC MMCs with some basic properties of the materials (TCF and TLEF) to compare our test data with the information from the literature sources

Light & Engineering
Vol. 27, No. 5, pp. 67–71, 2019 *https://doi.org/10.33383/2018-055*

THE CALCULATION METHOD FOR LIGHT CLIMATE PARAMETERS BASED ON SUN-LIGHTING EFFICIENCY AND THE COMPARATIVE ANALYSIS OF LIGHT CLIMATE IN HANOI AND MOSCOW

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ABSTRACT

The main source of daylight is the Sun. The Earth's atmosphere scatters its light due to the air, water vapour, ice particles (at high altitudes), dust, various gases, and other contaminants that appear in the air as a result of human activities. This forms a daylight diffuse (scattered) component, which is a data basis for calculation of daylight in buildings. This basis has its own features for a given region.

This article shows a calculation of sun-lighting efficiency in Vietnam. We obtained a variation of horizontal daylight illuminance in Hanoi (21.03°N). Comparing it with the variation of horizontal daylight illuminance in Moscow (55.70°N), we can see a high level and a distribution uniformity of outdoor illuminance in Vietnam. The maximum levels of diffuse illuminance and total illuminance in Hanoi are 45.2 and 58.52 klx; the maximum levels of diffuse illuminance and total illuminance in Moscow are 28.3 and 53.1 klx. Besides, illuminance levels in winter months are much higher for Hanoi than for Moscow. This can be explained by different latitudes of these cities and by the Sun motion.

Keywords: local light climate, tropical climate, diffuse horizontal illuminance, total horizontal illuminance, sun-lighting efficiency, cloud cover statistics

1. INTRODUCTION

Horizontal illuminance is an important factor of light climate resources in each region. At the present day, Vietnam offers no complete standards of computational methods for design of daylight in buildings. This paper contributes to the development of such standards and energy-efficient daylighting systems. This work also allows us to extend the available data on day-time changes in illuminance levels for all months in those Russian cities that are not included in the Daylighting Set of Rules and other reference materials.

The daylight factor *D* is used for rate setting of daylight/combined lighting indoors and for design of buildings and constructions. *D* is the ratio of daylight illuminance that is created by skylight, direct or reflected, at some point of a given plane indoors to a simultaneous value of outside horizontal illuminance that is created by light of a fully open firmament. We should mention that the notion *D* makes sense only under an overcast sky with a luminance distribution specified by the International Commission on Illumination (CIE). In this case, *D* does not depend on an orientation of the window with regard to the Sun, and this is a constant value for a given point of the room.

The overcast sky is not common for the tropics. Total sunlight and direct sunlight strongly affect the choice of a daylighting system indoors. Depending on the architectural solution of the enclosing structures using solar protection devices, direct sunlight gives more or less reflected light indoors. To assess the energy efficiency of daylighting systems for buildings in the tropics, the research of the light climate is required with regard to data on total horizontal illuminance and diffuse horizontal illuminance.

We do not have any data from field measurements of daylight illuminance in Vietnam at this time. The data on the light climate are calculated as per lighting efficiency of solar radiation with solar radiation satellite data. Lighting efficiency of solar radiation strongly depends on the current altitude of the Sun. Specifically, direct solar illuminance and lighting efficiency of direct solar radiation depend on the altitude of the Sun. The total (global) illuminance and the diffuse illuminance do not directly depend on the altitude of the Sun. The lighting efficiency of solar radiation is higher with diffuse lighting than with total lighting [1, 2].

Articles [3, 4] present 3 methods for calculation of lighting efficiency of solar radiation (including direct lighting efficiency, total lighting efficiency, and diffuse lighting efficiency of solar radiation) based on the corresponding mathematical models. To define lighting efficiency of solar radiation, we have chosen a model that was developed in Vietnam as part of this study [5]. This model was used to calculate daily variations in diffuse illuminance and total illuminance.

2. RESEARCH AND CALCULATION METHODS

ASHRAE IWEC2[1] weather data were selected to calculate the lighting efficiency of diffusive solar radiation (K_D) and the lighting efficiency of total solar radiation (K_Q) (lm/W). The software fills or reduces the data to hourly time steps and calculates the lighting efficiency level when converting the raw Integrated Surface Hourly Database to the local time. The data on the light climate of Hanoi accumulated for 12 years, from 2005 to the end of 2017, are typical. Meanwhile, the choice of typical months is based not only on average distributions but also on statistical distributions of different climatic parameters over months as per the records of long-term observations. The typical months selection method that is widely used to create first files of a typical meteorological year (*TMY*) was developed by the *NREL*[2] in the early 1980s (*NCDC*[3], 1981). The Finkelstein-Schafer (*FS*) statistics technique is used to select a *TMY*. Its main indicator is the *FS* value (statistics), which is determined by a total difference between a distribution of the candidate month and a long-term distribution in the same calendar months for the recording period. The *FS* statistics is evaluated with different climate parameters, which are later assigned with weighting coefficients and then summed. The month with the lowest *FS* value is considered the most representative typical month [6].

Wherein:

• The solar position is calculated by the formulas:

$$h_o = \arcsin\left\{\begin{matrix}\sin\delta\cdot\sin\varphi+\cos\delta\cdot\cos\varphi\times\\ \times\ \cos[15^0\cdot(12-T)]\end{matrix}\right\}, \text{deg},$$

$$\delta = 23.45\cdot\sin[\frac{360}{365}(d-81)] \text{ or}$$

$$\delta = 23.45\cdot\sin[\frac{360}{365}(284+d)], \text{deg},$$

where: d is sequential number of day of year, counting from January 1; h_o is Sun altitude, deg; δ is solar declination on any day of year, deg; T is time, h (e.g. 16h 15m = 16.25h); φ is latitude (south latitude with minus sign), deg;

• K_D and K_Q are calculated as follows:

$K_D = 0.1\cdot h_o + 67$, klx/(cal·cm^{-2}·min^{-1}),

$K_Q = 0.1\cdot h_o + 62$, klx/(cal·cm^{-2}·min^{-1});

• Diffuse illuminance and total illuminance are obtained by multiplying diffuse solar radiation data (cal·cm^{-2}·min^{-1}) by K_D and by multiplying total solar radiation data (cal·cm^{-2}·min^{-1}) by K_Q;

• K_D and K_Q are 70 and 65 klx/(cal·cm^{-2}·min^{-1}) or 101 and 93 lm/W in Hanoi according to this model.

3. RESULT ARGUMENTATION

It is obvious from the variation calculation results of diffuse daily illuminance and total daily illuminance in Hanoi and Moscow (compared by *the light climate* [7]) (Figs. 1, 2) that:

[1] *ASHRAE IWEC2* temporary files were developed for the American Society of Heating, Refrigerating and Air-Conditioning Engineers (*ASHRAE*) by *White Box Technologies, Inc.* These files are based on the integrated surface hourly database for 3,012 locations outside the US and Canada with ≥ 12-year (and ≤ 25-year) records. URL: http://weather.whiteboxtechnologies.com/IWEC2.

[2] *National Renewable Energy Laboratory*

[3] *National Climatic Data Centre*

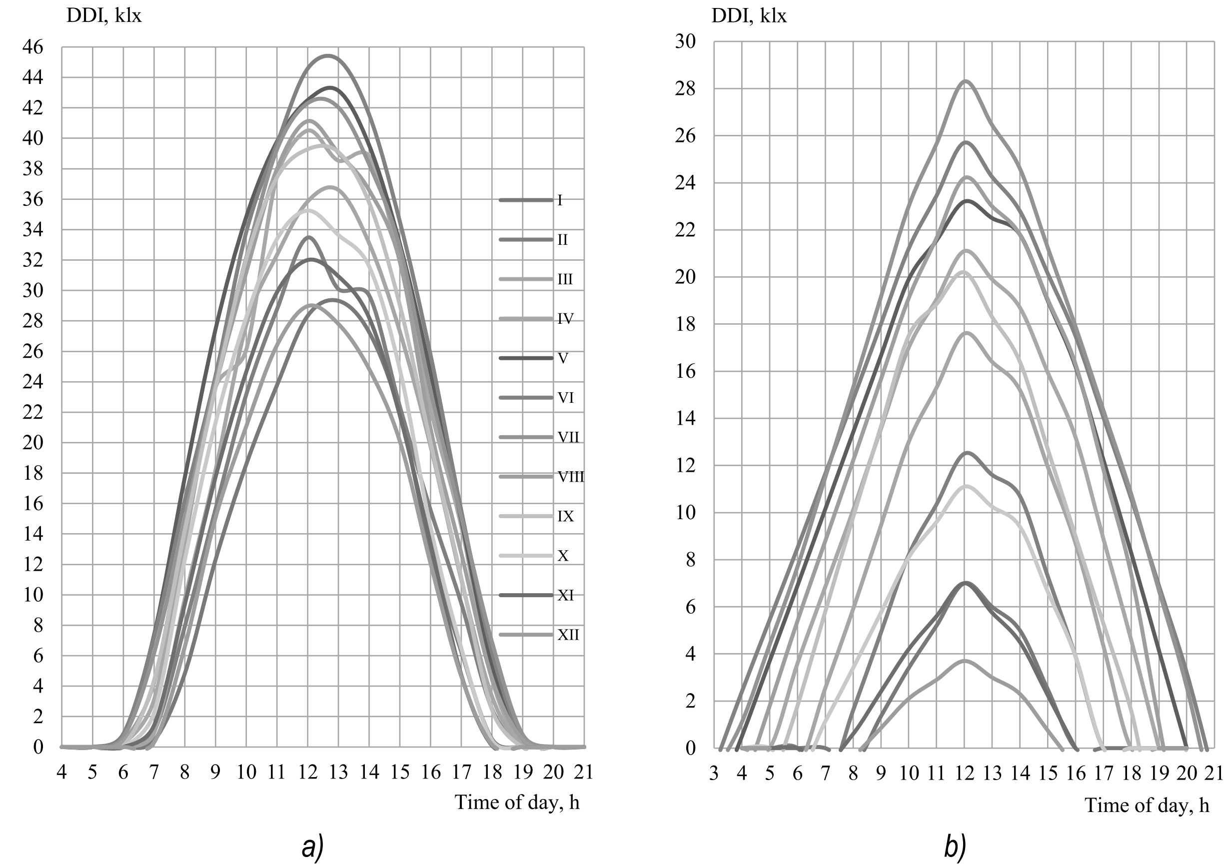

Fig. 1. Diagrams of variation in diffuse daylight illuminance (DDI) in Hanoi 21.3°N (*a*) and Moscow 55.7°N (*b*)

- Outer diffuse illuminance in Hanoi slightly varies between summer and winter months. The maximum diffuse illuminance level is 29 klx in winter periods (December) and 45 klx in summer periods (June). The high level of daylight horizontal illuminance in Hanoi is equally distributed within almost every month. Sunrise time is 05:15 (for June) and 06:35 (January). Sunset time is 18:39 (June) and 17:08 (December).
- The diagrams of diffuse daily illuminance variation in Moscow show a large difference in illuminance levels for winter and summer and a small duration of daylight for winter (from 08:23 to 15:27 for December) with the maximum level of diffuse illuminance of 3.7 klx. The longest duration of daylight for summer is 17h 30m (from 3:15 to 2:04 for June) with the maximum level of diffuse light of 28.3 klx.

The definition of daylight resources is very important for a design strategy of buildings in order to improve the energy efficiency of daylighting systems. The high level of daylight in Hanoi, with its equal distribution over months, allows daylight to use in this city all year round. The tropical climate, with large solar radiation, puts a large thermal load on building enclosures [8]. Therefore, daylighting systems featuring solar protection shall be widely used to reduce room heating during the summer period. Besides, solar protection devices weaken daylight illuminance in rooms by reducing direct lighting from the sky.

However, solar protection devices play a role of reflective panels at some point, which increase the level of reflected light indoors (with direct sunlight on these reflective panels). The research [9] carried out by the Moscow State University of Civil Engineering obtained *D* field results in a particular room of a building after installation of visor solar protection devices that show that the average *D* in a room with side light openings is 3.87 % under a clear sky with a total cloud cover of up to 2 points, which is higher than the average *D* under a cloudy sky that is 2.89 %. This means that solar-protected daylighting systems are more efficient in direct sunlight for tropical latitudes. To assess the energy efficiency of such systems, it is necessary to conduct a research of direct facade solar illuminance at different orientations and an impact

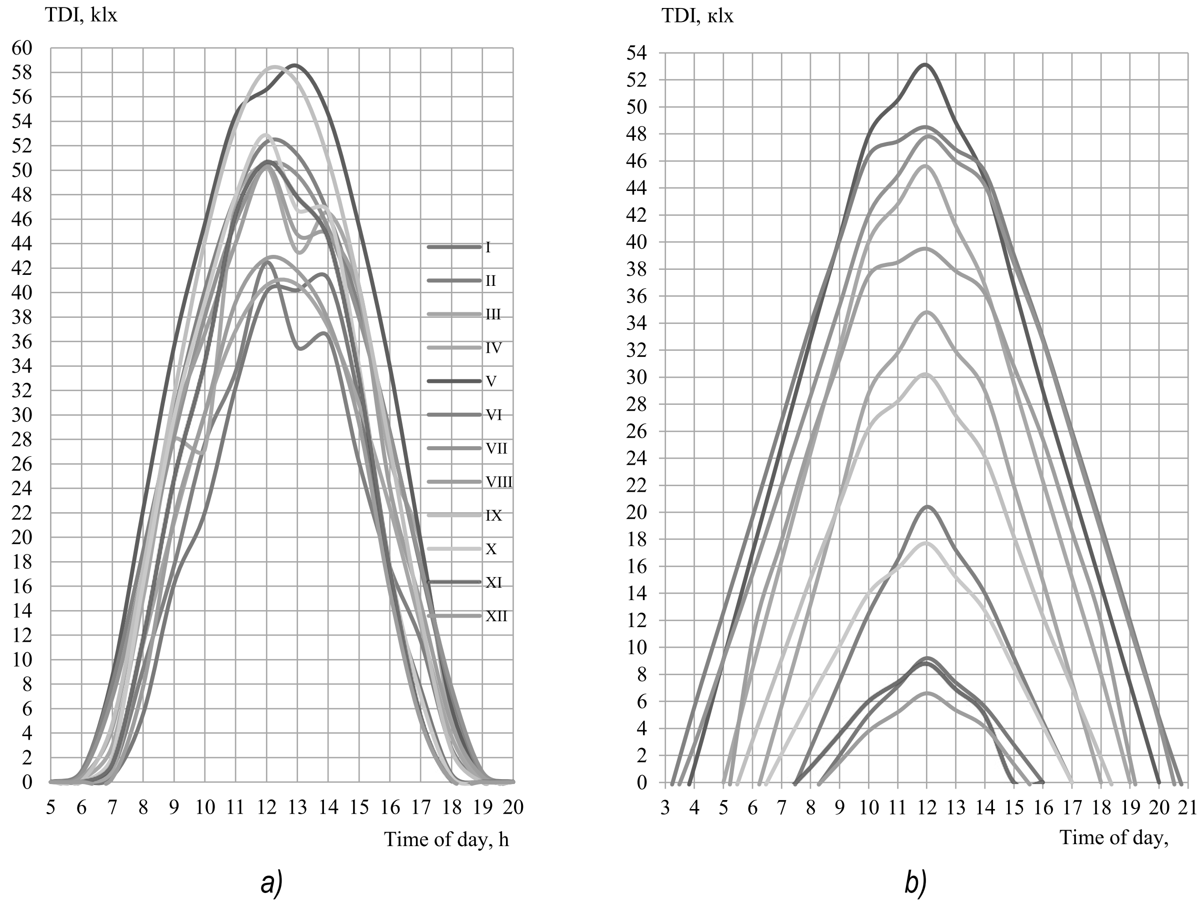

Fig. 2. Diagrams of variation in total daylight illuminance (TDI) in Hanoi 21.3°N (*a*) and Moscow 55.7°N (*b*)

analysis of various solar protection devices in daylighting systems of buildings.

Figs. 1, 2 show that consideration of total daylight for rooms featuring solar protection devices and other devices that exclude direct solar radiation could significantly improve the energy efficiency of daylighting systems in buildings without affecting the internal environment comfort of buildings not only in Hanoi, but also in Moscow.

CONCLUSION

The research of recent-years weather data and the analysis allow us to assess the light climate of the area and to obtain the materials for further studies of daylight in construction. The light climate resource data were obtained during the analysis of the survey results of daylight illuminance in Hanoi and Moscow. They show the illuminance distribution uniformity in Hanoi by months and the distribution nonuniformity in Moscow. At the same time, consideration of the total daylight illuminance with solar protection devices allows to reasonably assess the energy efficiency of daylighting systems even in the light climate of Moscow, which is actually much higher than the calculated efficiency with the assumption of a cloudy sky, according to the CIE. This allows us to consider the daylight in buildings to be a promising direction for improving the energy efficiency of buildings, especially in the tropical conditions of Vietnam, where various solar protection devices should be widely used. This allows not only to reduce the energy consumption associated with lighting, but to significantly reduce the thermal load indoors and the energy consumption associated with air conditioning.

The introduced technique allows us to calculate variation diagrams of diffuse illuminance and total illuminance in all cities of Vietnam and Russia, to clarify lighting and climatic factors, and to accept the regional daylighting standards at the modern level. Special field measurements of daylight horizontal illuminance will be carried out to determine the uncertainty of the calculation results.

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Light & Engineering
Vol. 27, No. 5, pp. 72–81, 2019
https://doi.org/10.33383/2018-068

VISUAL AND COGNITIVE ANALYSIS OF MULTIVARIATE DATA FOR CHARACTERIZING AL/SIC METAL MATRIX COMPOSITES

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ABSTRACT

The work shows the results of the literature review of the methods for obtaining aluminium-silicon carbide – metal matrix composites (Al/SiC MMCs). This work also includes the collection, analysis, and systemization of the literature data where textual information is presented as a single lexical and semantic system and where numeral information is presented as a dimensional system. The analysis of the literature data was conducted by visual and cognitive modelling, so that methods of forming Al/SiC MMCs and operating parameters that provide the best properties of the material (maximum level of thermal conductivity and minimum level of thermal linear expansion) are determined. Compared to the literature data, the data are presented that were received in a series of tests for obtaining Al/SiC MMCs with spark plasma sintering from SiC, which was synthesized in atmospheric electric arc plasma. Within the framework of the given subject, the authors do not know any analogues of such an analysis and visualization system that allows us to analyse multivariate data, which is essential for solving issues of finding a correlation for the variety of initial parameters that characterize the process of obtaining Al/SiC MMCs and that characterize the cluster of properties for the obtained material. The comparison data are given for thermal conductivity levels of modern (aluminium) LED light devices and Al/SiC MMC samples.

Key words: literature review, data collection, data systematization, multivariate data, visual and cognitive model, heat-transmitting element of the light device, Al/SiC MMC, properties, obtaining methods, conditions

1. INTRODUCTION

Light devices consume a large proportion of the world's electrical power generation, which constitutes about 19 % by various estimates [1]. The search for ways to reduce the energy consumption of light devices without damage to their useful quality can be considered as one of the main tasks of light engineering. Besides, the development of new and the improvement of current processes in manufacture of LEDs and LED light devices are in progress. The essential factor preventing such a development is the issue of effective heat transmission from LED light devices [2]. The use of metal matrix composite materials based on aluminium and silicon carbide (Al/SiC MMCs) in heat-transmitting elements of illumination device can solve this issue.

The most important properties of Al/SiC MMCs are a relatively high thermal conductivity factor (TCF), (100–200) W/(m·K) (standard conditions), and a low thermal linear expansion factor (TLEF), about $(8–9)\cdot 10^{-6}$ K^{-1} [3]. Thermal, physical and mechanical properties of Al/SiC MMCs significantly depend on a number of factors: SiC volume ratio; the morphology and the average size of SiC particles; the relative density and the porosity of the material; the phase composition and the grain size distribution of other impurities; the method of moulding and processing feedstock for a specific product. The difference in directions between individual studies on obtaining and analysing properties of Al/SiC MMCs does not allow a holistic approach to form for accelerating the search of metods for this material production with the given properties of production of this material (its product) with the given properties. The comprehensive cross-disciplinary researches for properties of Al/SiC MMCs can serve as a methodological background for science-based processes in manufacture of heat-transmitting elements for power-operated electrical tools, including high power LED illumination devices [4]. A literature review on methods and properties of Al/SiC MMCs usually contains text and/or numerical data as tables and one-dimensional dependences that link pairs of individual properties of Al/SiC MMC and one of the parameters that characterize the obtaining of this material as in other review papers [3, 4]. An important issue about finding necessary regularities and prediction of material properties, including for Al/SiC MMCs, is their representation as a set of one-dimensional dependencies such as $y=f(x_1)$, $y=f(x_2)$ (etc.). However, the arguments of these functions can be characterized by physical links, including non-obvious links. The number of analysed parameters can be about 5–10. The sets of analysed parameters are not completely overlapping or complete when matching within the results of studies. As a result, a comparative analysis with the use of analytical methods is very constrained.

We offer to use visual analytics means that were successfully used in a number of practical problems for the analysis of multidimensional empirical data to overcome this difficulty [5, 21]. In this case, visual models that use features of visual perception for cognitive interpretation of multidimensional data are proposed as the means of visual analytics. The visual model is a perceptual pattern compared with the initial data on a predefined rule, a metaphor of visualization, the interpretation of which leads to an answer hypothesis to the research question. The method of visual analytic means allows performing a verification of such hypothesis with interactive control of the visual model.

The modern review works on this subject show a fragmentary nature of studies devoted, as a rule, to solution of a particular task in order to achieve the required properties of material based on Al/SiC MMCs by changing a parameter [4]. According to the published survey works in this field, it is important to conduct comprehensive cross-disciplinary researches that link the properties of products based on Al/SiC MMCs not only with the composition (chemical, phase, particle size) and the structure, but also with the method of its obtaining and the features of the applied modes. The development of a multivariate visual model for the analysis of heterogeneous data for a comprehensive assessment and a prediction for properties of Al/SiC MMCs and the development of graphic methods with a cognitive component in the analytics is light an extremely relevant goal, the solution of which is required to develop processes for creation and application of heat-transmitting elements based on Al/SiC MMCs for the use in power-operated tools, including light devices.

The method of visual cognitive analysis of multivariate heterogeneous data is applied in this work, which is information from native and foreign literature about methods of obtaining Al/SiC MMCs and their properties [5]. As a result, the model was created with Autodesk 3D Max, the validity of which was validated by obtaining Al/SiC MMCs with spark plasma sintering (SPS). However, the developed model is not intended to be based completely on information from domestic and foreign literature. This model does not have any essential restrictions for expansion of the initial data and their continuous replenishment. In such a manner, the developed model can become a new method of storage, analysis and validation of test data (in this context, data of Al/SiC MMCs) and a constantly updated alternative to occasionally conducted review researches.

2. METHODS

A feature of the initial data studied in this work is a large number of heterogeneous sources of information that are represented by publications containing information about test researches in the given field. The heterogeneity and inconsistency of information are associated with this circumstance. The search and the selection of articles from domestic and foreign publishers containing information about methods of obtaining Al/SiC MMCs and its properties were carried out during the preparation for the analysis of the initial data. It should be noted that the authors at this stage of research do not claim any completeness of the information presented in their model with reference to all key authors working in the field of Al/SiC MMCs. The table was filled during the analysis of the literature data, containing the following fields: the record number (1); the number of the initial data source as per the reference list (2); the year of publication (3); the country of organization affiliated to the first co-author (4); the temperature T [K] at the measurement of properties for Al/SiC MMCs (5); the TCF of the material λ [$W\cdot m^{-1}\cdot K^{-1}$] (6); the TLEF δ [ppm[1]] (7); the SiC volume ratio v [%] (8); the relative density of the obtained material ρ [%] (9); the average particle size of SiC additive χ [μm] (10); the forming method of Al/SiC MMCs (11); the moulding temperature Ts [K] (12); the moulding pressure Ps [MPa] (13); the moulding time t_s [min] (14); the operating current I [A] of the moulding unit for Al/SiC MMCs (15); the data type: experimentally measured or modelled and calculated (the main part of these data is presented in Table 1).

We can see that there are three main categories of the data from the structure of the table: numerical data, text data, and absent data. The numerical data were reduced to one dimension and rounded when added to the table. If the author pointed out a range of values, the range boundaries were put in two different lines in the table. The dependence numbering was conducted by several points if there were characteristic curves not mentioned in the text of this work. The approach to the introduction of data on the bimodal distribution of SiC particles by size was not made during this research due to the fact that the division of data into two lines seems to be incorrect as the indication of the range. As a result, it was decided to indicate the arithmetical value of two modes of particle size distribution in the table. There is one similar source of information in the presented data.

The text data were added in as a result of the analysis of the lexical and semantical core of the subject: e.g. different types of impregnation (infiltration), under high pressure, in a discharged environment, and other varieties (sub-methods), were combined into a single concept of Infiltration. In addition, the search for a common textual concept was carried out. E.g. the names of the countries are given as a two-letter international code.

Dash (–) was added in case of absence of any data in the table. If any data is determined which are not relevant for the author but which obviously can be deduced from the context of the work, the dependencies, and the arguments, such data were put in the relevant field. E.g. if there are no data on the temperature of Al/SiC MMCs at the measurements of the thermal conductivity, the value of the ordinary room temperature (25 °C) was taken. If experimental dependences and approximating lines were mentioned, the test points were added to the table as measured data, and the points determined from the approximated data outside the test data range were added as simulated data.

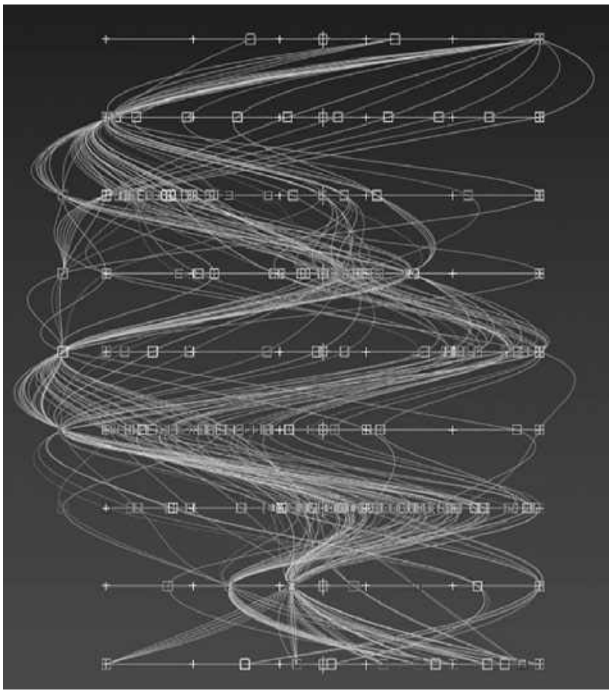

Fig. 1. The diagram of multivariate data that describes properties of Al/SiC MMCs (TCF and TLEF) depending on the method of composite forming, the volume ratio and the average size of SiC particles (year of the result included)

As a result of the analysis of literature sources, the data from the sources were included in the initial data table for the construction of the model [6–19]. In addition to the literature sources, this table of initial data contains the data about the test studies carried out to obtain Al/SiC MMCs with IPS using SiC obtained in atmospheric electric arc plasma [20] (cubic modification βSiC, 99 % pure, average particle size = 12μm).

The visual model created to solve the problem of the literature sources analysis (Figs. 1–3) serves as a spatial implementation of the parallel coordinates method offered for visualization of multivariate data [21]. In accordance with the visualization metaphor, a set of points in the space of the visual model united in an ordered graph is com-

[1] 1ppm = $1{,}000{,}000^{-1}$.

pared with each informative object containing published information about a separate test study. The interpretation of the information given in the visual model uses the processes of item visual comparison and such patterns of perception as the principles of constancy, integrity and generality.

The benefit of the visual model suggested in this work is simultaneous representation and reflection of different types of data in the perceived image, including multivariate data or data with missing values of some variables. The interactive control of properties of the obtained data allows defining/creating a hypothesis of the study during the analysis. This allows to repeatedly use the ready-made image (visual model) of the data, including for answers to new questions.

3. RESULT AND DISCUSSION

3.1. Al/SiC MMC Properties

Fig. 1 presents the diagram of multivariate data containing information about the properties of Al/SiC MMCs: the dependencies of the TCF and the TLEF from the composite forming method, the volume ratio, and the average SiC particle size. There is also a chronological scale for assessing the dynamic properties of the subject development over time. The timeline scale of the diagram covers the last 25 years. During the analysis of data distribution over time, we can conclude within the analysed works that the main method of forming Al/SiC MMCs was the method of infiltration 25 years ago (in its different manifestations, depending on the pressure). The infiltration moulding of Al/SiC MMCs is competing with the SPS within the analysed data during the last 15 years. SPS units that were relatively rare until the last decade are more used in the production of bulk MMCs.

According to the analysed data, TCF is (40–252) W/(m·K), mainly (118–252) W/(m·K). This range goes beyond the properties of aluminium not modified by SiC, both towards greater or less thermal conductivity. In this regard, we can conclude that the modification of aluminium with SiC does not always increase the TCF of the final composition within the framework of the presented analysed works due to the porosity of the formed Al/SiC MMC, the irregularity in the distribution of the ceramic component, its non-optimal phase and particle size distributions.

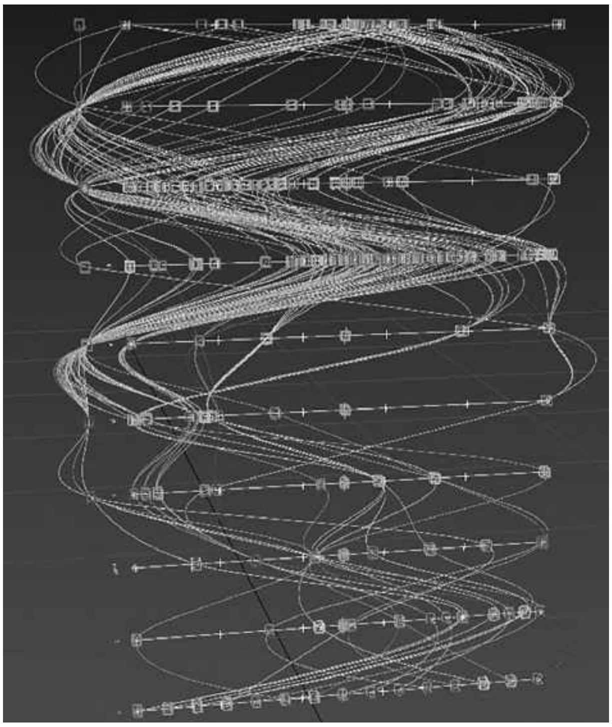

Fig. 2. The diagram of multivariate data that links the conditions and the methods of forming volume AL/SiC MMCs with some basic properties of the materials (TCF and TLEF)

We could portion the considered data array corresponding to the highest values of the TCF within the framework of the concerned model: (220–252) W/(m·K). This range of the TCF matches a series of data for the other axes that can be considered optimal to achieve the maximum TCF: density = (99–100) %, SiC volume ratio is in the range (38–70) %, average SiC particle size is equal to (100–125) μm. The parameter part determines the best quality of the material by its thermal conductivity. Some of the parameters can affect each other: e.g. the higher the volume ratio of SiC, the more difficult it is to obtain a volume material with a density of (99–100) %. According to the analysis, the part of these data is the result of calculations for the properties of the idealized Al/SiC MMC. The other part is obtained with tests.

We should note that the concerned data set that corresponds to the highest calculated and experimental levels of the TCF simultaneously matches the arguable range of TLEF values (13–17) ppm. This indicates a serious lack of knowledge in the fields of optimizing the composition, the structure and the properties of Al/SiC MMCs. The dominant majority of calculation and test works in the considered field shows the properties of Al/SiC MMCs at normal temperatures, which do not fully reveal the potential of this composite under thermal cycling in a wide temperature range that corresponds to possible extreme operating conditions of Al/SiC MMCs.

The selection of the data array that is characterized by the lowest value of the TLEF (about 5–6 ppm) mainly matches to the TCF ranges of (150–170) W/(m·K) and the SiC volume ratio of (71–100) % (we should note that the range is represented by its boundaries, 70 and 100 %, within the model). Besides, the selection of this array corresponds to the lack of data on the density of the material (mainly) and on the average particle size of Si C. Based on the set of the analysed data on the main properties of Al/SiC MMCs, we can conclude that we cannot achieve the maximum thermal conductivity at the minimum thermal linear expansion with standard methods and with imperfect processes for the production of this composite. This problem is obviously based on the correlation between phase and particle size distributions of Al/SiC MMCs: the highest content of SiC (at the limit, up to 100 % of the SiC ratio) provides the lowest TLEF. The moulding (sintering) of the material with the dominance of the SiC ratio at the relatively low pressure and at the relatively low temperature does not ensure a high level of relative density (about (99–100) %).

The analysis of moulding conditions is given in the next subsection of this article.

3.2. Conditions and Methods for Obtaining Al/SiC MMCs

The analysis of the diagram of multivariate data (Fig.2) shows the dominance of two methods in forming Al/SiC MMCs: SPS and infiltration.

The typical sintering temperatures usually are (813–883) K at the pressures of (40–60) MPa as a part of the SPS method. The typical sintering time within this method is (5–10) min. The pressure of about 300 MPa is applied in some cases with the sintering time of up to 37 min. The highest TCF values as a part of this method are achieved at the highest pressure and with the longest sinter time, but the obtained samples have average TLEF levels of around (10–17) ppm. We can find that the potential of Al/SiC MMCs today was not implemented with the SPS method on the level of the specified properties.

Many test samples were obtained with infiltration. The process usually flows at the temperatures of (973–1173) K that are higher than with the SPS method and at the relatively low pressures: about (1–2) MPa, in some cases up to 10 MPa. The process time is about 30 min. From all the works we analysed, we can single out the work [7] where the minimal TLEF of (5–6) ppm corresponds to the TCF of (225–250) W/(m·K) . These samples were obtained at the highest pressure we considered, 10 MPa, and at the relatively low temperature of 1023 K. The volume ratio of SiC was about 70 % in the sample. The parameters of the above test can be considered close to the optimum within the infiltration method. However, the work [7] has a number of other features: the authors first sintered SiC to a continuous 3D (volume) porous structure at 2673 K. As a result, the issue of the average size of the particles in the sample is ambiguous. SiC is represented in pictures taken by a focused beam microscope (within the resolution limits) in the form of a continuous monolithic structure. After such a structure, the pores in the sample are filled with molten aluminium at a pressure of the environment gas of 10 MPa.

On the one hand, this approach allowed us to keep the smallest TLEF, which was ensured by a frame of continuous integral (polycrystalline – as we can see) substance of SiC, the pores of which are filled with molten aluminium. The relative density of the sample is not specified in the work [7] due to the complexity of its determination in the chosen synthesis approach. We can conclude that the achievement of good properties is possible during the infiltration method for Al/SiC MMCs at the low TLEF of (5–6) ppm and at the TCF up to about 250 W/(m·K) with the SiC ratio of about 70 %. However, the variety of this method, which provides excellent key figures, is relatively complex and consists of several stages where a continuous volume porous structure of SiC plays a key role.

3.3. Test Research for Obtaining Al/SiC MMCs with the SPS

4 samples of Al/SiC MMCs were sintered within this work that had different weight fractions of SiC (2.5, 12.5, 25.0 and 50.0 %) with the SPS (through SPS10–4 by GT Advanced Technologies, USA). The basic substance was the powder of the

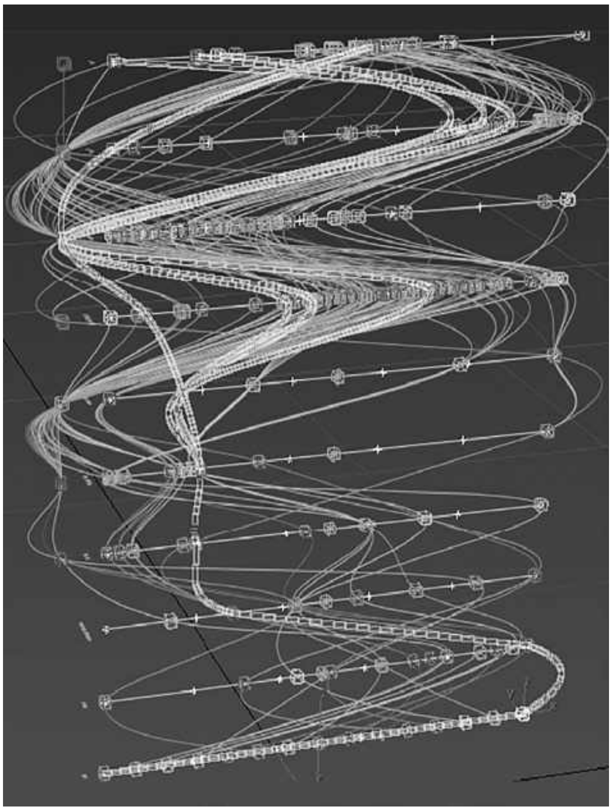

Fig. 3. The diagram of multivariate data that links the conditions and the methods of forming volume AL/SiC MMCs with some basic properties of the materials (TCF and TLEF) to compare our test data with the information from the literature sources

SiC cubic phase (βSiC) with an average particle size of about 12 μm and the commercial aluminium powder. SiC was obtained in the direct-current arc atmospheric plasma with the method developed at the National Research University – Tomsk Polytechnic University. The samples were sintered at the temperature of 833 K for 10 min and at the pressure of 60 MPa. The samples were studied with an X-Ray Diffractometer Shimadzu XRD7000s, a Scanning Electron Microscope Jeol JSM 5700F and a Laser Thermal Conductivity Meter TA Instruments-DLF 1200.

Based on the data in Fig. 3 that are in the form of the visual and cognitive analysis, the results were experimentally obtained and they corresponded to the results that are typical for the SPS: The TCF was (115–190) W/(m·K) for three samples with a lower SiC ratio and about 55 W/(m·K)[1] in a sample with the highest SiC ratio. Such levels of thermal conductivity, the applied method and the mode parameters are consistent with the worldwide-published data with due regard to phase and particle size compositions of the obtained images.

3.4. Assessment for Applications of Heat-Transmitting Elements Based on Al/SiC MMCs in Illumination Tools for the Achieved Thermal Conductivity

The aluminium-based radiators that are used for LED device cooling can feature the TCF of (150–200) W/(m·K) [22, 23]. The modern domestic and foreign heat-transmitting elements that are based on Al/SiC MMCs can feature the TCF of (150–170) W/(m·K) (some foreign elements can achieve up to 200 W/(m·K)) [15]. According to the studied literature sources, the highest achieved TCFs of Al/SiC MMC samples are (220–252) W/(m·K), which is higher than the TCFs of typical aluminium radiators used for LED cooling. Such a level of thermal conductivity allows for reliable and long-term operation of a single LED50 W or a group of close-packed LEDs, each 3 W [22, 23]. The heat-transmitting elements based on Al/SiC MMCs are suitable for use in LED illumination devices. The relatively low TLEF of high-filled Al/SiC MMCs allows for use of the tools in extreme ranges of thermal cycling, e.g. in the Arctic.

4. CONCLUSION

The collection, the systematization and the analysis of literature sources were made in this research that concern the methods of obtaining Al/SiC MMCs, their properties, the properties of heat-transmitting elements of LED illumination devices. The feature of this study is the approach that is based on a visual and cognitive model, which contains an array of multivariate heterogeneous text and numerical data. The developed visual model allowed: 1) to show the multivariate heterogeneous data with the use of the cognitive capacity of the user; 2) to identify the properties of the most common synthesis methods for Al/SiC MMCs (within the existing literature), the operating moulding parameters, as well as the phase and particle size distributions that provide the best results for the TCF and the TLEF. The model also included the data that were obtained during the test study of Al/SiC MMCs, which confirmed the main literature data. The visual model also allowed us to create new hypotheses to study the obtaining methods for Al/SiC MMCs and their properties. The authors today do not know any cases of such approach to the processing, the analysis and the storage of data on certain materi-

Table 1. The Main Data Used for Modelling*

Literature Source	*λ*, W/(m·K)	*δ*, ppm	*v*, %	*ρ*, %	*x*, µm	Molding Method	*Ts*, K	*Ps*, MPa	*ts*, min
[6]	210	24	0	100	–	–	–	–	–
	239	17	40		110	SPS	873	300	37
	247	15	45						
	252	14	50						
	246	13	55	99					
	208	12	60	98					
	–	10	70	–	–				
	–	5	100	–	–				
[7]	182	9	46	–	–	Infiltration	1023	10	–
	250	7	54	–	–				–
	250	6	63	–	–				–
	225	5	70	–	–				–
	140	10	46	–	–				–
	175	9	54	–	–				–
	180	8	63	–	–				–
	170	7	70	–	–				–
[8]	130	11.2	50	99	23	*Hot press*		55	15
	135	11.6		99	38				
	141	12.1		97	75				
	140	10.8		99	23				
	148	11.2		99	38				
	156	11.5		97	75				
[9]	38.5	–	50.4	97	8	Plasma spraying	–	–	–
	50.6	–	52.7	98	11		–	–	–
	69.8	–	51.6	98	17		–	–	–
	71.4	–	38.8	99	30		–	–	–
[10]	153	–	–	–	0.3	Infiltration	973	0.4	–
	155	–	–	–					–
	154	–	–	–					–
	156	–	–	–					–
	157	–	–	–					–
	162	–	–	–					–
	163	–	–	–					–
[11]	200	23	0	–	–		–	–	–
	170	16.4	25	–	–		–	–	–
	135	10.4	55	–	–		–	–	–
	105	6.2	70	–	–		–	–	–
	80	5	100	–	–		–	–	–

Literature Source	***λ*, W/(m·K)**	***δ*, ppm**	***v*, %**	***ρ*, %**	***x*, μm**	**Molding Method**	***Ts*, K**	***Ps*, MPa**	***ts*, min**
[12]	221	–	58	–	167	Infiltration	1023	0.28	30
	209	–	58	–	86.4			0.34	
	203	–	60	–	56.8			0.40	
	204	–	59	–	37.1			0.50	
	194	–	58	–	23.4			0.60	
	193	–	55	–	16.9			0.78	
	154	–	53	–	8.9			2.1	
[13]	190	–	0	–	100		–	–	–
	225	–	70	–			–	–	–
	237	–	70	–			–	–	–
	180	–	–	–	20		–	–	–
	210	–	–	–	50		–	–	–
	220	–	–	–	200		–	–	–
[14]	208	–	55	100	40	SPS	833	50	5
	211	–	60	100			833	50	
	204	–	58	97.4			833	45	
	185	–	56	92.8			833	40	
	192	–	56	93.7			823	45	
	165	–	53	87.5			813	40	
	220	–	50	100	100		833	50	
	224	–	55	100			833	50	
	208	–	58	96.3			833	45	
	197	–	55	91.2			823	40	
	181	–	53	88.7			813	45	
	173	–	52	86.6			813	40	
[15]	158	4.97	70	–	125	Infiltration	–	–	–
	162	5.14		–			–	–	–
	161	5.32		–			–	–	–
	156	–		–			–	–	–
	154	5.97		–			–	–	–
	150	6.31		–			–	–	–
	149	–		–			–	–	–
[16]	177	9.5	50	98.9	48	Casting	1073	50	–
	172	7.89	58	99.3	48				–
	138	7.74	71	97.5	28**				–
	125	6.33	71	97.8					–
	123	6.54	71	97.1					–
[17]	165	9.2	70	–	40			100	–

<table>
<tr><th>Literature Source</th><th>λ, W/(m·K)</th><th>δ, ppm</th><th>v, %</th><th>ρ, %</th><th>x, µm</th><th>Molding Method</th><th>Ts, K</th><th>Ps, MPa</th><th>ts, min</th></tr>
<tr><td rowspan="6">[18]</td><td>190</td><td>10</td><td>50</td><td>–</td><td>28</td><td rowspan="9">Infiltration</td><td rowspan="6">1073</td><td rowspan="6">50</td><td>–</td></tr>
<tr><td>125</td><td>7.5</td><td rowspan="5">70</td><td>–</td><td>28</td><td>–</td></tr>
<tr><td>150</td><td>6</td><td>99.5</td><td>–</td><td>–</td></tr>
<tr><td>140</td><td rowspan="3">7.5</td><td>99</td><td>–</td><td>–</td></tr>
<tr><td>135</td><td>98</td><td>–</td><td>–</td></tr>
<tr><td>120</td><td>97</td><td>–</td><td>–</td></tr>
<tr><td rowspan="3">[19]</td><td>146</td><td>10.5</td><td>39</td><td rowspan="3">99</td><td rowspan="3">6</td><td rowspan="3">1173</td><td rowspan="3">0.1</td><td>–</td></tr>
<tr><td>136</td><td>9.24</td><td>52</td><td>–</td></tr>
<tr><td>118</td><td>8.45</td><td>62</td><td>–</td></tr>
<tr><td>–</td><td>188</td><td>–</td><td>0</td><td>98</td><td rowspan="4">12</td><td rowspan="4">SPS</td><td rowspan="4">883</td><td rowspan="4">60</td><td rowspan="4">10</td></tr>
<tr><td>–</td><td>120</td><td>–</td><td>16.9</td><td>96</td></tr>
<tr><td>–</td><td>131</td><td>–</td><td>21.4</td><td>97</td></tr>
<tr><td>–</td><td>54</td><td>–</td><td>53.6</td><td>86</td></tr>
</table>

* The data in the table may differ from the data given in the sources due to the conversion into a single system of dimensions, rounding and adding to the table the data that are the conclusion of the authors of this work based on the analysis of the primary source.
** The given value is the arithmetic mean value of the limits for the bimodal particle size distribution.

als, their properties, methods and operating parameters of their production. They also believe that the method of visual and cognitive modelling is applicable to solve any search-related analytical problems in different subject fields.

ACKNOWLEDGEMENT

The work was made with the financial support from the Russian Science Foundation, Project No. 18–11–00215.

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Light & Engineering
Vol. 27, No. 5, pp. 82–87, 2019
https://doi.org/10.33383/2018-111

ANALYSIS OF THE LUMINOUS FIELD IN FLUORESCENT OPTICAL LAYERS WITH QUANTUM DOTS BASED ON *CDSE/CDS/ZNS*

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ABSTRACT

The structure of a luminous field in a fluorescence layer containing *CdSe/CdS/ZnS*-based quantum dots and acting as a transducer[1] in an optical fluorescent sensor is described on the basis of three-flux approximation. Differential equation system of three-flux approximation is solved by numerical technique. It is found that diffuse reflectance[2] of the layer extremely depends on concentration of quantum dots in the layer and its physical thickness. Optimal parameters of the layer required for forming of maximum analytical layer are determined.

Keywords: optical sensors, fluorescence, quantum dots, optics of fluorescence layer

One of directions of development of contemporary analytical chemistry is development of sensor devices allowing to make operative analysis with high precision in real time with minimal sample preparation. Such devices have been being introduced in medicine, biology, biochemistry and ecology [1–3] for analysis of both gaseous and liquid media. Of special interest are optical fluorescent sensors which are characterised with simplicity, multi-purposes, high sensitivity and precision of measurements.

Development of contemporary methods of synthesis of new types of semi-conductor colloid phosphors based on cadmium and zinc chalcogenides like *CdSe/CdS/ZnS* – the so-called quantum dots (QD) – has opened new prospects in development of a generation of optical sensor devices of this type. These substances have a number of unique optical and physical and chemical properties, primarily high photostability and energy-efficient fluorescence in visible and near infrared regions of spectrum.

One of important distinctions of the reviewed QD's is high dependence of their fluorescent properties on chemical environment. For example, experience has shown that these properties are very sensitive to interfacial processes proceeding in case of adsorption of molecular oxygen, water, ammonia, hydrogen chloride, hydrogen peroxide, molecular bromine, and iodine, and many other substances on the surface of quantum dots (see, for example, [4–7]). Despite high practical importance, the mechanisms of the fluorescence quenching processes are not studied well currently [8], but it does not prevent application of QD's for our purposes. Besides, we have found that not only the level of fluorescent radiation is subject to sufficient changes in various media, but also electrophysical properties (in particular, dielectric losses, dielectric capacity and conductance) are [9].

The processes of fluorescence quenching are the most interesting processes for application in sensors as they reduce radiation by sensitive layer. Among the most efficient quenchers, there are ions of heavy

[1] Transducer is a device transforming visible changes (of physical or chemical nature) into a measurable signal [1].

[2] All light engineering magnitudes in the article are implied to be spectral ones. – Ed. Note.

metals, halogens in molecular form, paramagnetic ions and molecules as well as acceptors of electron excitation [10]. Effect of fluorescence quenching by means of molecular iodine I_2 was used by us for development of a fluorescent sensor based on this entity [11]. The quenching effects were used also in structures of sensors for analysis of a number of chemical entities: hydrogen peroxide, ions of heavy metals, molecules of halides, colourants, polar solvents, and many others.

During manufacturing of a sensing element, QDs are introduces in suitable matrices (both polymer and porous non-organic ones). The prepared sensing layers should be placed in a measure cell allowing to perform excitation and registration of photo luminescence and probably to study some of its other properties such electrical (and dielectric), dielectric capacity, dielectric conductance and dielectric losses. What is critically important here is that the sensitive layer should be available for target external influence such as contacts with analysed gaseous or liquid medium and irradiation by exciting radiation as well as for correct registration of emitted radiation. A laser or a LED with required radiation wavelength may be used as a source of exciting radiation. A typical structural diagram of a sensor is shown in Fig. 1.

This article describes calculation of luminous fields in a sensitive layer of a transducer in order to determine optical characteristics required for obtainment of optimal analytical signal such as concentration of photoactive component, optical thickness of a layer, radiance of exciting radiation, capability to diffuse light and conditions of reflection from the borders of a layer. The target parameter here is radiance of the emitted (upwelling) radiation in direction of a radiation detector.

Then, to obtain radiance of radiation reflected from a flat optical layer, we use some representations of multi-flux approximation. For instance, for a non-fluorescent infinite flat layer, it is possible to use two-flux approximation proposed by M.M. Gurevich [12] and then developed by P. Kubelka and F. Munk [13] where a field may be described by the following system of differential equations:

$$\begin{aligned} \frac{dI_1(x)}{dx} &= -(k+s)I_1 + sI_2(x), \\ \frac{dI_2(x)}{dx} &= sI_1(x) - (k+s)I_2(x) \end{aligned} , \qquad (1)$$

where k and s are absorption and diffusion indexes, $I_1(x)$ and $I_2(x)$ are radiances of incident and upwelling radiation inside a layer in a plane with x coordinate.

The system (1) has an analytical solution [14] which, in particular, derives general reflectance of a flat layer μ with physical thickness d:

$$\ln\frac{(\mu - a - \sqrt{a^2-1})\left(\mu' - a + \sqrt{a^2-1}\right)}{\left(\mu' - a - \sqrt{a^2-1}\right)\left(\mu - a + \sqrt{a^2-1}\right)} = 2kd\sqrt{a^2-1},$$

where μ' is the reflectance of the upper border of the layer and $a = 1 + s/k$.

Then we use a three-flux Kubelka-Munk model where distribution of radiation inside a medium (layer) is represented as differential-difference equations for three components of this radiation according to [15, 16]:

$$\frac{dF_1(x)}{dx} = -(k+s)F_1(x),$$

$$\frac{dF_2(x)}{dx} = -\{2k + \frac{3}{4}[k + s(1-g)]\}F_2(x) + \\ + \frac{3}{4}[k + s(1-g)]F_3(x)] + \frac{s}{4}(2+3g)F_1(x), \qquad (2)$$

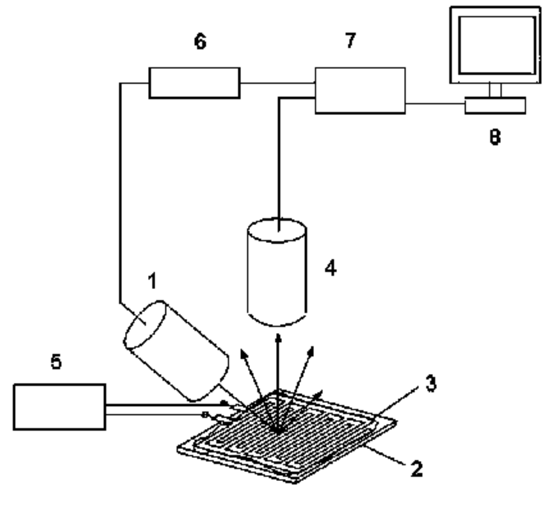

Fig. 1. Diagram of the fluorescent sensor for simultaneous measurements of radiance and a number of electrophysical parameters of the fluorescent sensitive layer: *1* – the source of exciting radiation; *2* – coplanar cell with interdigitated structure on a neutral base; *3* – sensitive layer; *4* – diffused radiation detector; *5* – dielectric characteristics measuring device; *6* – exciting radiation source (LED or laser) control unit; *7* – spectrometer; *8* – computer

$$\frac{dF_3(x)}{dx} = \{2\text{k} + \frac{3}{4}[k + s(1-g)]\}F_3(x) -$$
$$-\frac{3}{4}[k + s(1-g)]F_2(x) - \frac{s}{4}(2-3g)F_1(x),$$

where $F_1(x)$ is the radiance of collimated exciting incident radiation, $F_2(x)$ is the radiance of diffused incident radiation, $F_3(x)$ is the radiance of diffused upwelling radiation, g is the diffusion anisotropy factor.

The boundary conditions for this system are as follows:

$$F_1(0) = (1 - r_{1,\text{фр}})F_{10}\ ,$$

$$F_2(0) = (1 - r_{1,\text{фр}})F_{10} + r_{\text{вн}}F_3(d)\ ,$$

$$F_3(d) = r_{\text{вн}}F_2(d)\ ,$$

where F_{10} is the radiance of collimated exciting incident radiation at the upper border of the layer, $F_3(0)$ is the radiance of diffused upwelling radiation at the upper border of the layer, $F_2(d)$ is the radiance of diffused incident radiation at the lower border of the layer, $r_{1,\text{фр}}$ is the Fresnel reflection coefficient, $r_{\text{вн}}$ is the internal reflectance of both borders of the layer.

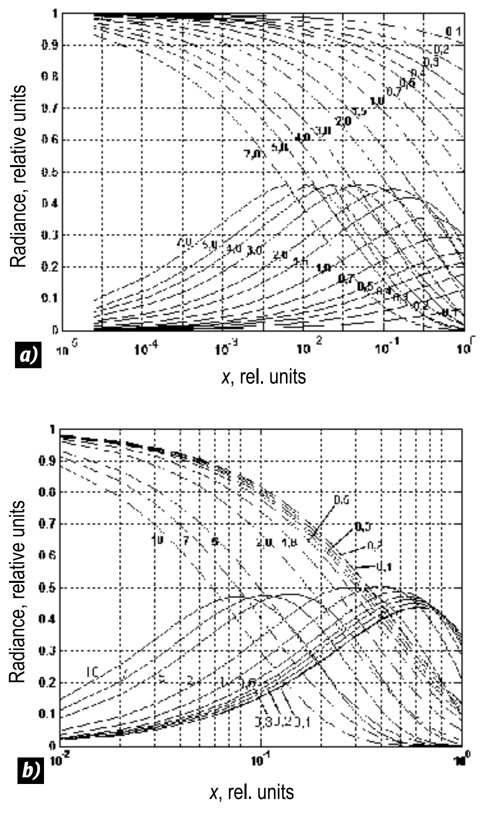

Fig. 3. Luminous field in a non-diffusing, $s = 0$ mm^{-1}, (*a*), and diffusing, $s = 2$ mm^{-1}, (*b*), fluorescent layers. The dashed lines are the curves of radiance of collimated exciting incident radiation $F_1(x)$, continuous lines are curves of radiance of diffused upwelling radiation $F_3(x)$ forming the analytical signal of the transducer. The numbers near the curves are the relevant values of k (mm^{-1})

It is worth noting that, unlike the system (1), the system (2) doesn't have an analytical solution and reflectance coefficients included in it may be calculated using relevant Fresnel formulas [17].

Introduction of phosphor in the layer sufficiently complicates distribution of radiation inside it. Herewith, the system of equations (2) should be supplemented by item *f*(x):

$$f(x) = \frac{1}{2}k_1\,\text{f}\cdot[F_1(x) + F_2(x) + F_3(\text{x})]\,,$$

where k_1 is the absorptance at wavelength of fluorescence excitation, f is the fluorescence quantum efficiency.

It can be noted that introduction of QD's as a photoactive component causes intensive absorption in the blue region of spectrum. Peak of radiation in a used fluoropolymer matrix is near excitonic absorption (Fig. 2). Addition of fluorescent component to the equation system (2) gives the following result:

$$\frac{dF_1(x)}{dx} = -(k+s)F_1(x)\,,$$

$$\frac{dF_2(x)}{dx} = -\{2k + \frac{3}{4}[k + s(1-g)]\}F_2(x) +$$
$$+\frac{3}{4}[k + s(1-g)]F_3(x)] + \frac{s}{4}(2+3g)F_1(x) + \qquad (3)$$
$$+\frac{1}{2}fk_1[F_1(x) + F_2(x) + F_3(x)],$$

$$\frac{dF_3(x)}{dx} = \{2k + \frac{3}{4}[k + s(1-g)]\}F_3(x) -$$
$$-\frac{3}{4}[k + s(1-g)]F_2(x) - \frac{s}{4}(2-3g)F_1(x) +$$
$$+\frac{1}{2}f\cdot k_1[F_1(x) + F_2(x) + F_3(x)].$$

Analytical solution of the equation system (3) is impossible and its computational solution was performed using *MATLAB ode45* procedure with relative accuracy of 0.1 % specified by default (The procedures of solving differential equations using this software are well-known [18]).

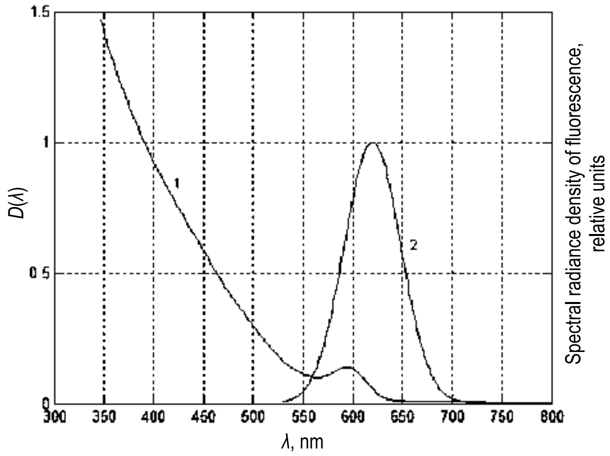

Fig. 2. Spectral optical density (*1*) and spectral radiance of fluorescent radiation (*2*) of the sensitive layer based on the fluorine-containing polymer film containing *CdSe/CdS/ZnS* quantum dots

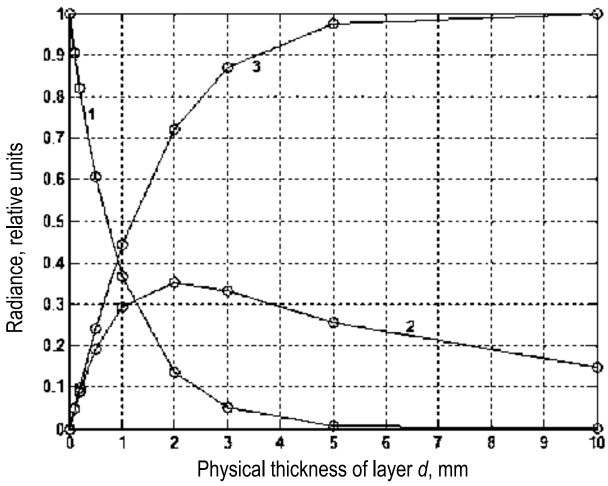

Fig. 4. Dependences of boundary radiances of radiation $F_1(d)$ (*1*), $F_3(0)$ (*2*) и $F_2(d)$ (*3*) on physical thickness of layer *d*

Analysis of radiation distribution in the fluorescent layer, in particular, allowed us to optimise light-converting layers used as cover materials [19] and to obtain major conformities of formation of chromaticity of optical materials containing *CdSe/CdS/ZnS* QDs with different wavelength of upwelling radiation [20]. The results of calculations performed in this study show, in particular, that the analytical function $F_3(x)$ has extremum nature (Fig. 3). The example presented in Fig. 4 shows that the level of a relevant analytical signal characterised with a value of $F_3(0)$ is maximal with physical thickness of layer equal to 2 mm. (Increase of thickness in excess of this value causes reduction of signal amplitude, which is thought to be important for development of fluorescent sensors).

The calculations made show that, in order to amplify the signal F_{30}, it is necessary to optimise the value of *s*, which is rather practicable, so the matrix should be porous for efficient operation of transducer. Consideration of absorption of exciting radiation as well as fluorescent flux by the photoactive component shows that $F_3(0)$ is extremum depending on both concentration of QDs in the matrix and *d*. Measurements using a sensor with a sensitive layer based on a porous fluorine-containing co-polymer has shown that optimal concentration of QDs is 1.5 mg/g with thickness of the sensitive layer of 2 mm. Increase of concentration of the photoactive component and *d* as compared to these values causes reduction of $F_3(0)$, i.e. general reflectivity of the layer.

CONCLUSION

1. Analysis of a luminous field of a sensitive element of the fluorescent sensor based on *CdSe/CdS/ZnS* quantum dots has been performed. The computational scheme based on the system of three differential equations considering radiances of incident exciting, incident diffused and general upwelling radiation has been used.

2. Computational methods of solving the equation system have been developed and the structure of the luminous field in the layer has been determined. Major conformities of formation of radiance of general upwelling radiation, which should be used for formation of an analytical signal of a sensor, have been found.

3. It has been found that radiance of the general upwelling radiation of a layer is extremum dependent on both concentration of QDs in the material and on physical thickness of the sensitive layer. Optimal dimensions of the sensitive layer required for its efficient application as a transducer has been proposed.

ACKNOWLEDGMENT

The study was performed with financial support of the Ministry of Education and Science of the Russian Federation. Grant Agreement 14.574.21.0185 (ID of applied scientific research (project) RFMEFI57417X0185).

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Light & Engineering
Vol. 27, No. 5, pp. 88–96, 2019
https://doi.org/10.33383/2018-063

OPTICAL METHOD OF DETECTION OF OIL CONTAMINATION ON WATER SURFACE IN UV SPECTRAL RANGE

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ABSTRACT

Efficiency analysis of optical (photo and radiometric) method of oil contamination detection based on differences between reflective characteristics of clean and oil-contaminated water surfaces was conducted with sounding wave selection in UV, visible, near-infrared and medium-infrared regions of the spectrum. It is shown that, in terms of eye safety, width of thickness interval of detected oil films and atmospheric attenuation, the most promising type of sounding for monitoring of oil contamination is UV sounding at a wavelength of 0.355 μm, which allowing to detect oil films with thickness of at least 2 μm reliably with probability of correct detection exceeding 0.9 and probability of false alarms of 0.002 with relative measurement noise not exceeding 5 %.

Keywords: remote optical method, vision-safe radiation wavelengths, UV region of spectrum, oil contamination on water surface, detection

1. INTRODUCTION

The problem of environmental protection, first of all, the air and water environment, is one of the most important problems nowadays [1–6].

One of the top positions among contaminants of oceans, seas, lakes, and rivers of our planet is taken by oil and products of its processing. The main factors of oil contamination of sea, lake, and river spaces are disasters with vessels (especially tankers), offshore oil industry, oil pipeline accidents (especially at crossings of rivers, channels, lakes, and reservoirs), damage of underground oil product storages and leakages of their content, river flows, etc. [2, 4, 7–10].

In terms of frequency and volume of oil spillage, the most dangerous are accidents with oil carriers and accidents during offshore oil production as well as accidents with oil pipelines, oil storages, and oil products (when spillages are detected by monitoring instruments). In these cases, the fact of emergency spillages of oil is usually known, and the objective of mapping the oil stain and control of its evolution over time rises.

No less important is the objective to detect oil contamination, when spillages cannot be detected by monitoring instruments and in case of different accidents when corresponding information is not announced. For prevention of environmental consequences of such contaminations, it is preferable to detect them as soon as possible.

The topic of the article is the development of operative remote optical (photo and radiometric) detection method of oil contaminations on the water surface.

2. PROBLEM FORMULATION

A rapid growth of contamination of water environment with oil products results in necessity to develop the methods and equipment for their timely detection.

Remote methods that allowing to inspect large areas during a small period and to conduct both detection and mapping of contaminations comply with all requirements to oil contamination detection means to the fullest extent.

For operative remote detection of oil contaminations on the water surface, especially for near-shore regions of seas and during the early phase of spillage, planes fit the most.

Spillages of oil can be remotely detected using both passive and active methods [4, 10–20].

Using passive methods, solar radiation reflected from the sea surface, thermal radio radiation of surface in the microwave region or thermal radiation in the infrared region of the spectrum are registered. However, all passive methods of detection have disadvantages. Application of the first method is possible only during daytime and only in case of good weather, the main disadvantage of the second one is impossibility to detect films with thickness of less than 100 μm, and the disadvantage of the third one is that the temperature contrast between oil contamination and clean surface of water strongly depends on thickness of the film, hydrometeorological conditions, and period of the day and maybe both positive and negative.

With active methods, some radiation source is used for irradiation of the sea surface, e.g. radar station or optical radar. Detection of oil contaminations by radar method is based on decreasing of HF components of heaving by the oil film. Its main disadvantage is that there are other areas with lowered heaving on the sea surface (not related to oil contamination), which may be caused by subsurface waves, films of surface-activated substances, wind shadows behind islands or steep shore, etc. Therefore, the problem of distinguishing the areas of oil contamination from other surface areas with lowered heaving arises. Moreover, in case of still air and gentle wind, the radar method is not able to detect oil contaminations (in such conditions, there are no rips on the surface or those are very low). Detection of oil contaminations by active optical methods is possible throughout the day and is based on the difference between reflective or fluorescent characteristics of clean and oil-contaminated water surfaces.

The reviews of optical sounding systems state that their main disadvantage is strong dependence on atmospheric conditions. It is true if we speak about all optical sounding systems in general. However, this disadvantage is significantly mitigated for aviation systems (the atmosphere is non-isotropic along the vertical, and the main contribution in radiation attenuation is made by a relatively thin (50–100) m surface layer.

Nowadays, there is a number of known active optical methods of oil contamination detection. For example: 1) the fluorescent method allowing to detect oil contaminations on water surface, to measure thickness of oil films, and to categorise them, but the sounding distance (height) of the most of fluorescent lidars does not exceed (100–150) m; 2) the method of active optical detection based on differences of reflective characteristics of clean and oil-contaminated water surface, which is efficient for detection of oil contaminations. Its advantages are relative simplicity of equipment and capability to perform sounding from large heights.

The analysis of existing detection methods of oil contaminations of water surface [4, 10–20] shows that the equipment of remote optical sounding is the most efficient variant for an operative system of oil contamination monitoring. At the same time, integration of fluorescent radar with an optical locator allowing to perform analysis of reflective characteristics of the water surface from a height of several kilometres (with bigger flight height, the plane equipment provides larger monitoring strip on the water surface) is considered promising [4, 10].

Therefore, this article describes the development of a photo and radiometric detection method of oil contaminations on the water surface at a sight-safe wavelength (λ) of sounding.

3. OPTICAL METHOD BASED ON THE DIFFERENCE BETWEEN REFLECTIVE CHARACTERISTICS OF CLEAN AND OIL-CONTAMINATED WATER SURFACES

The physical basis of oil contaminations detection by the optical method is the contrast of the registered radiant flux of radiation reflected from the clean water surface and water surface with oil contamination.

The contrast is caused by two factors: oil contaminations increase reflectance (e.g. at $\lambda = 1.06\ \mu$m, the reflectance value of the clean water surface is equal to about 0.02, and the reflectance value of a thick oil film is about 0.04), and oil films lower heaving of the water surface [4, 21–24].

The contrast between the clean water surface and the oil-contaminated water surface K is usually determined using the formula:

$$K = \frac{P_{\text{oil}}}{P_{\text{w}}},$$

where P_w and P_{oil} are values of power of signals registered on the clean water surface and the oil-contaminated water surface respectively.

The formula of this contrast may be obtained using the formula of the average power registered by the optical radar in the course of the monostatic sounding of the wavy water surface:

$$K = K_V K_{\gamma,\sigma}, \quad (1)$$

where $K_V = \frac{V_2^2}{V_1^2}$,

$$K_{\gamma,\sigma} = \frac{\left(\gamma_{1x}^2 \gamma_{1y}^2\right)^{\frac{1}{2}}}{\left(\gamma_{2x}^2 \gamma_{2y}^2\right)^{\frac{1}{2}}} \exp\left\{-\frac{q_x^2}{2q_z^2}\left[\frac{1}{\gamma_{2x}^2} - \frac{1}{\gamma_{1x}^2}\right]\right\}$$

$$\left[\frac{\frac{\tau^2 c^2}{16} + 2\sigma_1^2 + \sin^2\theta / (C_s + C_r)}{\frac{\tau^2 c^2}{16} + 2\sigma_2^2 + \sin^2\theta / (C_s + C_r)}\right]^{\frac{1}{2}},$$

$q_x = 2\sin\theta$, $q_z = 2\cos\theta$, θ is the sounding angle (between the direction of the optical radar optical axis and the nadir direction), σ^2 and $\gamma_{x,y}^2$ are dispersions of heights and inclinations (along some of x and y axes) of heaving, V^2 is the reflectance of the flat (without heaving) area of the water surface, τ is the duration of the radar impulse, $C_{s,r} = (\alpha_{s,r} L)^{-2}$ (for transparent atmosphere), $2\alpha_{s,r}$ is the divergence angles of the radiation source and the field of view of the receiving optical system, L is the flight height.

The values of V, γ, σ with index 1 are related to the clean water surface and those with index 2 are related to the oil-contaminated water surface.

While obtaining the formula (1), it was presumed that the spindrift is not generated (the wind velocity is low), the inclinations of the water surfaces are low: $\gamma_{x,y}^2 << 1$, $\alpha_{s,r}^2 << \gamma_{x,y}^2$, the size of the illumination spot on the surface and the heaving height of the water surface are low as compared to L.

It should be noted that the formula (1) is obtained using the expressions for the average received power. Since the pulse repetition rate of the plane lidar may be equal to hundreds of Hz and even tens of kHz, the size of water surface areas, on which received power is averaged may be equal to first tens of metres even with high speed of the plane. For instance, with pulse repetition rate of 1 kHz and plane speed of 100 m/s (ordinary speed for measurements), in the registration time interval of 0.1 s (which is equal to 10 m along the flight route), 100 impulses will be accumulated (which is quite enough for estimation of the average value of the received power). The flight height is selected on the basis of the radiation source power (which, in its turn, depends on the pulse repetition rate) in this case.

In the formula (1): the term $K_{\gamma,\sigma}$ describes the contrast between the clean water surface and the oil-contaminated surface caused by lowering of the water surface heaving by the oil film; the term K_V describes the contrast between the clean water surface and the oil-contaminated surface caused by the difference between the values of reflectance of the clean water surface and the oil-contaminated water surface; the value V_2^2 is the reflectance of the three-layer-system “air–oil film–clean water surface” and the value V_1^2 is the reflectance of the two-layer-system “air–clean water surface”.

The formulas for V_2^2 and V_1^2 have the following form (see, for instance, [4, 21]):

$$V_2^2 = \left| \frac{(Z_1 + Z_2)(Z_2 - Z_3)e^{-i\alpha(\lambda)d} + (Z_1 - Z_2)(Z_2 + Z_3)e^{i\alpha(\lambda)d}}{(Z_1 + Z_2)(Z_2 + Z_3)e^{-i\alpha(\lambda)d} + (Z_1 - Z_2)(Z_2 - Z_3)e^{i\alpha(\lambda)d}} \right|^2, \quad (2)$$

$$V_1^2 = \frac{(1 - n_2)^2 + k_3^2}{(1 + n_2)^2 + k_3^2}, \quad (3)$$

where $Z_j = \frac{2}{m_j}$; $\alpha(\lambda) = \frac{2\pi}{\lambda} m_2$; d is the thickness of the oil film on the water surface; n_j and k_j are the refractive and absorption indexes of j-th medium; $m_j = n_j + i \cdot k_j$ is the complex refractive index of j-th medium (for air, $m_1 = n_1 = 1$) and n_j and k_j are its real and complex parts respectively; the indexes 1, 2, 3 relate to air, oil, and water.

V_1^2 is defined only by the corresponding n_j and k_j, and V_2^2 complexly (due to the interference of radiation reflected from the air and oil film interface and oil film and water interface) depends on optical characteristics of water and oil products, λ of sounding and the thickness of oil film d.

Right after spillage of oil on the water surface (e.g. in case of an accident with oil pipeline or storage, wreck of oil carrier, etc.), the thickness of the film may be equal to several centimetres. Due to the

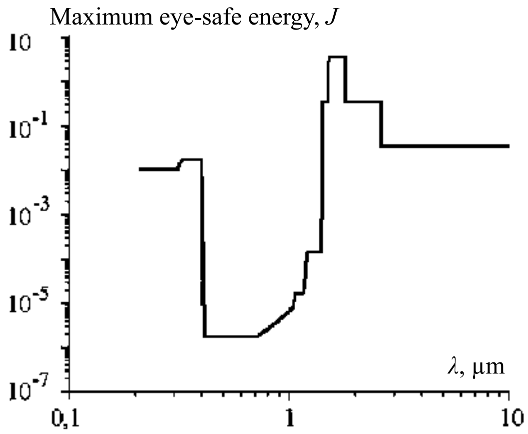

Fig. 1 Spectral dependence of maximum eye-safe energy of laser impulse

distribution of oil over the surface of the sea, the thickness decreases down to (1.0–0.1) mm and less. An important issue is the thickness of oil spillage after reaching of which the spillage stops being an integral whole [4]. Depending on oil grade, this thickness is usually estimated within the range between 4 and 100 μm. In the meantime, there are numerous data sets of thickness measurement of different oil and oil product grade films obtained both in-field and in laboratories, which obtained a lesser (than 4 μm) thickness of oil films [10].

In the simplest way, monitoring of oil contaminations is conducted registering the signal reflected from the water surface and determining the contrast between the level of power of the optical signal reflected from the clean water surface (which is registered, for example, while flying above clean water areas) and the one registered above the water surface along the flight route [4, 13, 25].

However, it is still not clear, which λ in the visible region is the most preferable for detection of oil contaminations: the contrasts between the clean water surface and oil contaminations complexly depend on λ, the thickness of oil film and type of oil product. Moreover, in the course of the development of optical equipment for remote sounding, it is necessary to take the degree of danger of laser radiation for sight into consideration.

4. SELECTION OF EYE-SAFE LASER RADIATION SOURCES

The functioning of active optical systems of remote sounding is always linked with danger to human organs of sight. However, the remote sounding system operates at still matters.

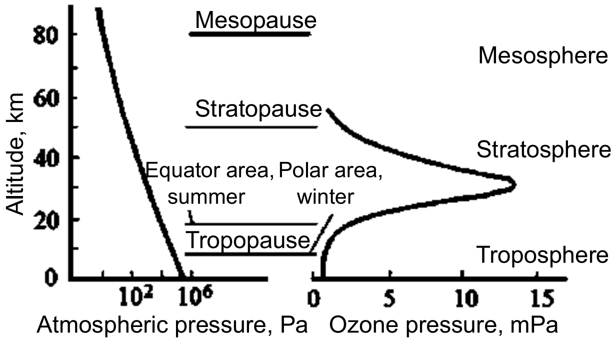

Fig. 2. Altitude distribution of atmospheric ozone

Radiation in visible and near-infrared spectral regions (0.38–1.4 μm) may cause damage to the retina and UV radiation within the range of λ of (0.18–0.38) μm and infrared radiation within the range of $\lambda > 1.4$ μm affect front ocular media and are considered safer [26, 27].

Fig. 1 [26] illustrates the safety of radiation for eyes at different λ (with equipment parameters specific for systems of active optical sounding, the pulse duration of 6 ns, the pulse repetition rate of 100 Hz and the optical beam diameter of 50 mm).

The requirement of eye-safety causes necessity of selection between UV (λ in range (0.18–0.38) μm), near-infrared, and medium-infrared ($\lambda >$ 1.4 μm) regions. The selection should be based on the efficiency analysis of application of these regions for detection of oil contaminations on the water surface.

In the said infrared regions, at λ>1.4 μm, due to high absorption by water and CO_2 vapours, the most promising λ of sounding are limited by atmospheric transparency windows of (1.5–1.8) μm, (2.1–2.4) μm (erbium-glass radiation sources, yttrium-aluminium garnet radiation sources with holmium addition, optical parametric oscillators) and (8–12) μm (CO_2-based radiation source).

Within the region of λ of (0.18–0.38) μm, due to absorption by oxygen and ozone (in the shortwave part of this region), the most prospective value of λ for remote sounding equipment is 0.355 μm (third harmonic of the yttrium-aluminium garnet radiation source with the addition of neodymium).

With pulse repetition rate ranging between hundreds of Hz and first kHz units and impulse duration of (5–10) ns, the impulse energy of the existing radiation sources with λ of 0.355 μm (e.g. *Ekspla NL230–100*) ranges between hundreds of μJ and first units of mJ, which allows us to perform sounding from the height of about several kilo-

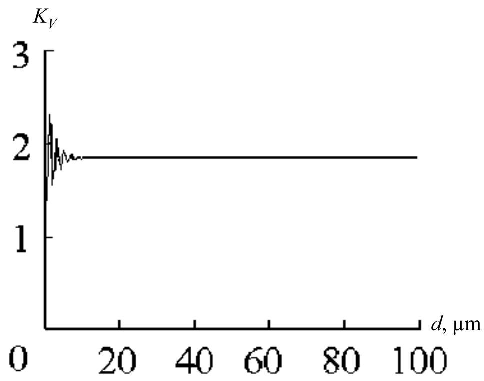

Fig. 3. Dependence of contrast K_V on film thickness *d* at λ of 0.355 μm

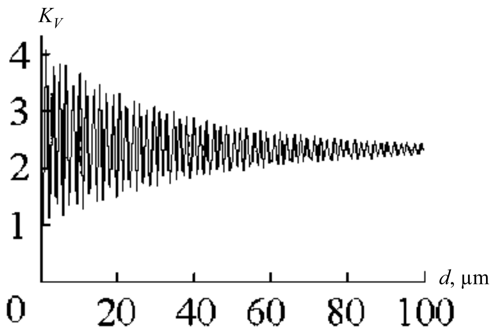

Fig. 4. Dependence of contrast K_V on film thickness *d* at λ of 1.54 μm

metres (with the receiving lens diameter of about (6–10) cm). The selection of the size of illumination spot on the sea surface is defined by requirements to the minimal detectable size of oil spillage on the sea surface.

It should be noted that UV spectral region is of interest for plane laser sounding systems as absorption of UV radiation by atmospheric ozone occurs mostly in the upper layers of the atmosphere. Fig. 2 [28] shows the general distribution of ozone in the atmosphere at different altitudes. In the lower layer of troposphere, the concentration of ozone varies depending on the place of monitoring but is maximum (units of mPa and less [29]).

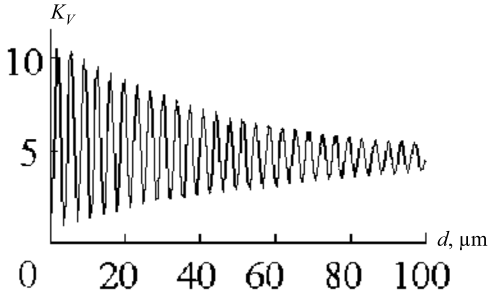

Fig. 5. Dependence of contrast K_V on film thickness *d* at λ of 10.6 μm

Below the contrasts between the clean water surface and oil contamination at eye-safe λ of sounding in a wide spectral band between UV and medium-infrared regions (0.355–10.6) μm are estimated.

5. ANALYSIS OF CONTRASTS BETWEEN CLEAN WATER SURFACE AND OIL CONTAMINATIONS AT EYE-SAFE RADIATION WAVELENGTHS IN UV, NEAR-INFRARED, AND MEDIUM-INFRARED SPECTRAL REGIONS

In Figs. 3–5, the dependencies of contrast K_V (caused by the difference of reflectance of the water surface covered with oil contamination film and the clean water surface) on the thickness of an oil film *d* at eye-safe λ of sounding of 0.355 m 1.54 and 10.6 μm respectively.

All the above-given figures show that, with an increase of oil contamination film thickness, the contrasts K_V oscillatory approximate some constant values, which are equal to contrasts of the two-layer medium “air–oil contamination” at corresponding λ. For sounding λ of 0.355, 1.54, and 10.6 μm, the values of this contrast equal to 1.84, 2.3, and 4.6 respectively.

Oscillatory nature of the dependence of contrast on oil contamination film thickness makes the operation of optical oil contamination detector (in real conditions of measurement noise) unstable in near-infrared and medium-infrared regions.

Fig. 6 shows the example of the mathematical modelling results of contrast dependence K_V on the thickness of oil contamination film *d* at sounding λ of 1.54 μm with a relative standard deviation of

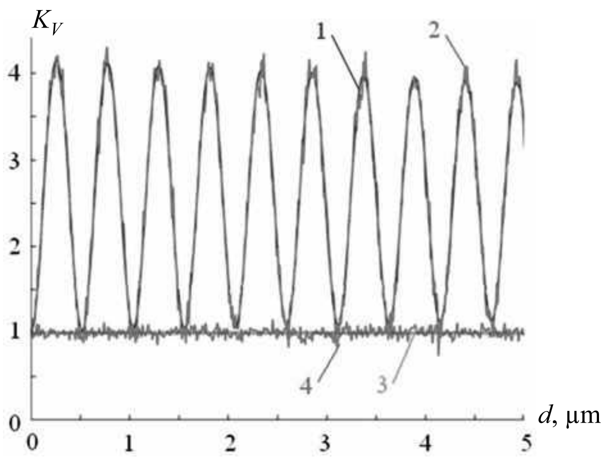

Fig. 6. Dependence of contrast K_V on oil thickness in conditions of noises with σ = 5 % at λ of 1.54 μm

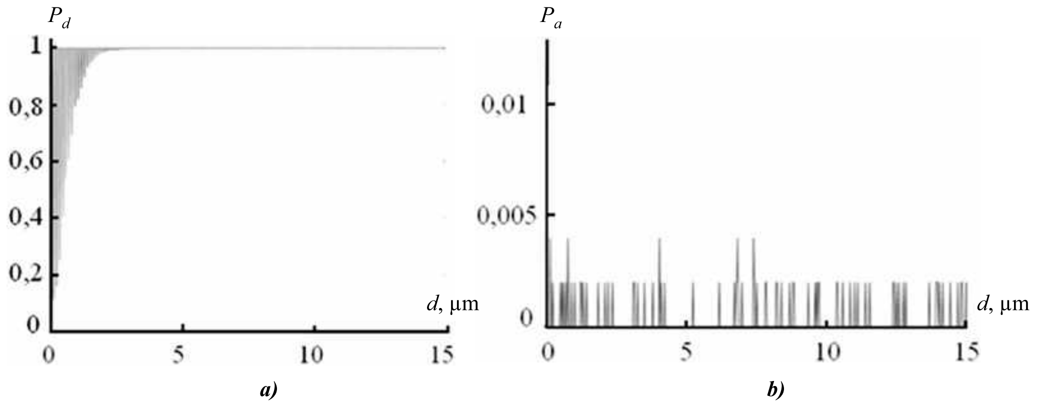

Fig. 7. Dependence of probabilities of correct detection P_d (*a*) and false alarms P_a (*b*) on oil film thickness at λ of 0.355 μm within the thickness interval of (0–15) μm

measurement noise of 5 %. In this figure, 1 stands for the contrast of oil contamination film without consideration of measurement noises, 2 stands for the contrast of oil contamination film with consideration of measurement noises, 3 stands for the contrast of the clean water surface $K_V \equiv 1$ without consideration of noises, and 4 stands for the contrast of the clean water surface with consideration of noises. It can be seen that, due to the noises, K_V of thin oil films occasionally becomes less than 1. At λ of 10.6 μm, this effect increases, it is seen to the least extent at λ of 0.355 μm.

Subsequently, despite the high values of the contrast of the two-layer medium "air–oil contamination" in the near-infrared and especially medium-infrared region, application of UV spectral region (λ of 0.355 μm) is more promising (in terms of reliability of measurements for thin oil films).

For estimation of operation reliability with measurement noises, mathematical modelling, and estimation of probabilities of correct detection and false alarms for detection of oil contaminations were conducted.

6. THE RESULTS OF MATHEMATICAL MODELLING OF OIL FILMS AND FALSE ALARMS CORRECT DETECTION PROBABILITIES

Mathematical modelling of correct detection probability P_d (probability of detection of oil contamination when it actually occurs) and probability of false alarms P_a (probability of detection of oil contamination when it does not actually occur) in conditions of measurement noises was conducted at eye-safe sounding λ in UV (0.355 μm) and near-infrared regions of the spectrum (1.54 μm).

The values of water and oil product refractive and absorption indexes at λ of 0.355 μm and 1.54 μm were taken from [21] (average characteristics of seawater and oil). It was assumed that measurement noise is normally distributed with zero average. The relative standard deviation of noises was set within the range of (1–10) %.

In the course of mathematical modelling, the values of oil films were set within the interval between 0.1 and 100 μm (thicker films are efficiently detected, for instance, by thermal radio methods). It was considered that the system of impulse active optical detection is capable (using spectral, spatial, and temporal filtering) to efficiently detect a signal among additive noises, and these noises influence the system operation only in the form of shot noise of photodetector (caused by it) [10]. Therefore, in the course of solution of the oil film detection task, the signals from the clean water surface and the oil-film contaminated surface registered by the receiver of the detector in conditions of noises were compared.

Availability of oil film was detected provided the condition $K_V > K_{th}$ was met (the contrast K_V between the studied area of the water surface and the invariably clean area of the water surface is higher than the threshold contrasts K_{th}). The value of K_{th} was selected (calculated before modelling) between 1 (the value of contrast when there are no oil-contaminations on the studied surface) and the minimal contrast (minimal value of K_V which is always more than 1) without noises and with set minimal thickness of films (which should be detected based on the remote sounding data).

Fig. 7 and Fig. 8 show the results of probability mathematical modelling of correct detection (P_d) and false alarms (P_a) with relative measurement

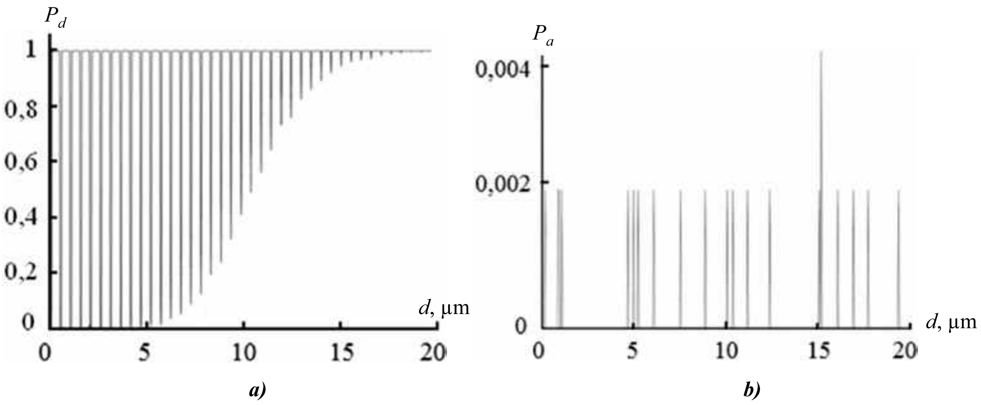

Fig. 8. Dependence of probabilities of correct detection P_d (*a*) and false alarms P_a (*b*) on oil film thickness at λ of 1.54 μm within the thickness interval of (0–20) μm

noise of 5 % (among 1000 samples of measurement noise) at sight-safe sounding λ in UV spectral region: at λ of 0.355 μm (Fig. 7, *a* and *b*) and in near-infrared spectral region: at λ of 1.54 μm (Fig. 8, *a* and *b*).

The figures show that with oil thicknesses more than 20 μm, probability of correct detection at sounding λ of both 0.355 μm and 1.54 μm is 100 %. However, in case of thinner films (which can be equal to units of μm and less) the situation is completely different: with sounding λ of 0.355 μm, it is possible to reliably detect oil films with thickness of at least 2 μm with acceptable P_d (more than 0.9) and P_a (less than 0.002) with relative measurement noise not exceeding 5 %. In the meantime, with sounding λ of 1.54 μm, P_d for oil films with a thickness of 2 μm may have any value ranging between 0 and 1 (depending on the random thickness of film in the sounding point).

7. Analysis of Oil Type Impact on Characteristics of Detection of Oil Contaminations on the Water Surface by Laser Method

The energy calculation of optical detector and mathematical modelling of P_d and P_a for detection of oil contaminations on the water surface are usually conducted for average characteristics of oil (see, for example, [4, 13, 25] and the above-listed results). However, different types of oil have significantly different optical characteristics.

For estimation of the impact of the oil type on the reliability of oil contaminations detection, mathematical modelling of P_d and P_a for different types of oil in conditions of measurement noises at sight-safe sounding λ of 0.355 μm was conducted.

It was assumed that measurement noise (during the registration of reflectance V_2^2 and V_1^2) is normally distributed with zero average and relative standard deviation δ =(1–10) %. Oil contamination was considered detected if the contrast $K_V = \frac{V_2^2}{V_1^2}$ was higher than K_{th}. The value K_{th} was selected between the value of K_V for oil contamination on the sea surface and $K_V = 1$ (the value of contrast for the clean water surface).

Table 1 (using formulas (1–3) and data from [30]) contains optical characteristics (*n* and *k*) and the results of mathematical modelling (among 1000 samples of measurement noise) of P_d and P_a with a thick oil film, relative standard deviation of measurement noise of 10 % and one threshold algorithm of detection for different types of oil. The types of oil products are given in the table line: 1 – diesel oil and 2–6 – different types of oil corresponding with different fields [30].

Table 1 shows that, despite P_d and P_a are different for different types of oil (with significant differences of *n* and *k*), these differences are non-significant.

Therefore, for detection of oil contaminations on the water surface by means of active optical detection at sight-safe λ of 0.355 μm, one detection algorithm may be used for all types of oil products.

8. CONCLUSION

Comparative analysis of efficiency of optical (photo and radiometric) method of oil contaminations detection on the water surface based on differences between reflective characteristics of clean and oil-contaminated water surfaces was conducted with sounding λ selection in UV, visible, near-in-

Table 1. The Results of Mathematical Modelling of Effect of Oil Type on Reliability of Detection of Oil Contaminations

Parameter	1	2	3	4	5	6
n	1.565	1.559	1.560	1.549	1.528	1.527
$k \cdot 10^3$	20.1	16.5	11.4	8.4	5.6	4.8
P_d	0.9991	0.9990	0.9989	0.9982	0.9967	0.9960
P_a	0.031	0.0308	0.0312	0.032	0.0338	0.0332

frared, and medium-infrared regions of the spectrum. It is shown that, in terms of eye-safety, the width of thickness interval of detected oil films and optical attenuation in the atmosphere, the most promising sounding method for monitoring of oil contamination is sounding in UV spectral region at λ of 0.355 μm. It allows to reliably detect oil films with a thickness of at least 2 μm with the probability of correct detection exceeding 0.9 and probability of false alarms of less than 0.002 with relative measurement noise not exceeding 5 %.

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Light & Engineering
Vol. 27, No. 5, pp. 97–102, 2019
https://doi.org/10.33383/2018-033

BISTATIC UNDERWATER OPTICAL-ELECTRONIC COMMUNICATION: FIELD EXPERIMENTS OF 2017–2018

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ABSTRACT

The article describes the results of experiments with underwater bistatic optoelectronic communication systems with scattered laser radiation as the source of information and the valid signal. The information reception distance of up to 40 m was gained in field conditions of lake water.

Keywords: natural water medium, bistatic optical communication, scattering, probabilities and SD of communication errors, photoelectronic multipliers

1. INTRODUCTION

The works [1–3] review capabilities and variants of development of underwater bistatic optoelectronic communication systems (OECS), which use scattered or reflected optical radiation (in particular, laser radiation) as the source of information and the valid signal[1].

Theoretical studies of transmitting properties of bistatic channels of OECS are being conducted within the frameworks of the theory of short-wave radiative transfer in scattering and dissipative media (such as the atmosphere and water media) and the theory of linear system analysis. The relation between radiance in a given point and in the given direction in a medium with the optical characteristics of the medium is determined by the radiative transfer equation which has the following integro-differential form:

$$\frac{1}{c}\frac{\partial I}{\partial t}+(\omega, grad\ I)=$$
$$=-\beta_{ext} I+\beta_{sc}\int_{\Omega} I(r,\omega')g(r,\omega,\omega')d\omega'+\Phi_0(r,\omega),$$

where $I = I(\lambda, r, \omega)$ is the radiance at a wavelength λ in point r in the direction ω; c is the light speed; $\beta_{ext}(\lambda, r)$ is the extinction coefficient at λ in point r; $\beta_{sc}(\lambda, r)$ is the scattering index at λ in point r; $g(\lambda, r, \omega, \omega')$ is the scattering indicatrix at the wavelength λ in point r in the direction ω; ω' is the direction of radiation before scattering; Φ_0 is the source function in point r in the direction ω.

This equation: *a*) is linear in relation to *l*, therefore the analysis of transfer properties of the bistatic communication channels is practicable to be performed within the framework of the linear systems theory, i.e. to study the channel reaction $h(t)$ for the input $\delta(t)$ impulse depending on the input parameters of OECS; *b*) does not have a general analytical solution, therefore different algorithms of the Monte Carlo method (from the forward modelling algorithms [4] to modifications of double local estimates [5]) are used for its solution for applications related to communicative underwater bistatic OECS.

The publications [6–10] overview the modelling results of impulse reactions of underwater

[1] Bistatic OECS are more often called *Non Los of Sight (NLOS)* OECS in literature, and sometimes those using reflected radiation as a valid signal are called *Direct NLOS* OECS, whereas those using scattered radiation are called *Non Direct NLOS* OECS

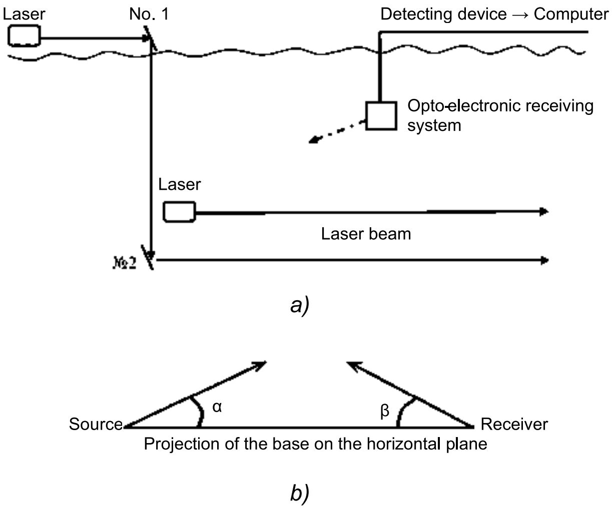

Fig. 1 Schemes of the experiments: *a* – side view: "green" laser on the lakeshore and "blue" laser in the water; *b* – plan view: direction of optical axes of the radiator and the receiving system

communication channels by means of the Monte Carlo method, with the help of which the maximum ranges of coverage of specific variants of underwater *Direct NLOS* OECSs were evaluated. Those were ranging between 5 and 100 m depending on the varied parameters of OECS and optical condition of the water medium. In [10], the impact of random wave tilts on the air-water interface on the OECS coverage range was taken into consideration, whereas in [9], the impact of optical-geometric conditions of bistatic channels formation on probabilities of communication errors was assessed.

The article [11] proposes an analytical model of the received bistatic signal, described the results of pool experiments with the distances between the source and the receiver (called basic) L of up to 50 m. Comparison of theoretical estimations of signal strength loss has shown that the proposed model is rather consistent with experimental measurements with L ranging between 10 and 50 m. On these routes, the signal loses its strength at (6–10) dB depending on the optical condition of water and orientation directions of the source and the receiver optical axes. The same work contains the results of experiments in the *Woods Hole Oceanographic Institution*, the USA, in the course of which underwater optical communication was performed in puddled water at distances of up to 40 m. The article [12] discusses the results of our first experiments with bistatic OECS[2] in the *natural water medium*.

2. EQUIPMENT, SCHEMATICS, AND THE RESULTS OF EXPERIMENTS

The goal of this work was to compare the range of coverage and quality of underwater communication (based on communication errors and standard deviation (SD)) on the basis of the field experiments of 2017–2018 conducted during tests of underwater bistatic OECS with various-spectra radiation sources and various average power in a *natural* water basin. Since these characteristics depend on the optical condition of water medium, it was of interest to compare them during tests in different periods of the year (in winter, when the water is less puddled and in spring, when the lake receives aerosol from the atmosphere and wastes from the surrounding territory.

A detailed description of the methodology of the experiments of 2017–2018 and the equipment used for them is given in [14]. Let us briefly repeat it. As impulse radiation sources, a "green" laser based on the vapours of cupric bromide (peak λ = 510.6 nm) developed by IAO SB RAS and a "blue" laser module *B2000* (peak λ = 445.0 nm) switched to impulse mode were used. Real-time probing of communication channels quality was performed based on estimations of sample average values and SD of communication errors. For this purpose, a test periodical graphic signal was transferred via the communication channels. The experiments of 2015–2016 were conducted both in water medium and through the ice into and out of the water [12].

The average power of the impulse "green" laser during the 2017–2018 experiments was equal to (4–6) W and that of the "blue" one was equal to (13–20) mW, laser beam divergence did not exceed 1° and 2° within the field of sight of the receiving system.

The orientation schematics of receivers and sources of radiation implemented during the experiments are shown in Fig. 1.

The place of the experiment was the Boyarskoye lake near Tomsk. According to [16, 17], it may be proposed that the Boyarskoye lake is eutrophic with optical characteristics close to those of the water of the Lapa lake in Altai Krai. Like the Boyarskoye lake, it is a closed lake, a dead stream branch located in the vicinity of the city. The experiments with the "green" laser were conducted in Febru-

[2] Field studies of bistatic OECS in the atmosphere are described, for instance, in [13–15].

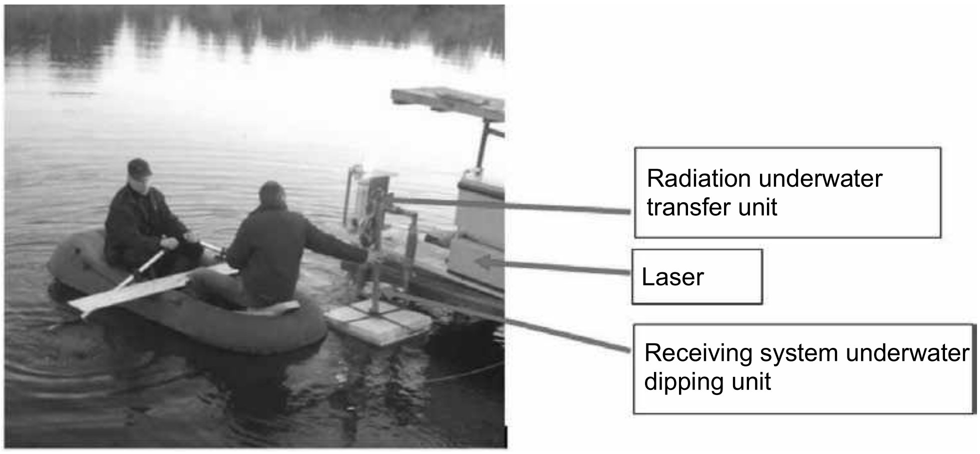

Fig. 2. Photo of the experiment participants moving the receiving unit across the lake and main units of the OECS laboratory set

ary and May, 2017. Input of the "green" laser radiation in winter was performed by means of two mirrors, No. 1 and No. 2 (Fig. 1, *a*) through a hole in the ice (the ice thickness reached 50 cm, the depth of the lake in the experimental areas is 6 m). The impulse frequency of the laser radiation was 11 kHz, their duration was (20–40) ns. In 2017, the receiving unit included an FEU-84 photoelectronic multiplier. The receiving unit was dipped in the water through the hole in the ice to the distance of up to 70 cm from the lower ice border. The results were obtained for *L* ranging between 5 and 25 m and are discussed in [13]. The distinction of the geometrical scheme of the underwater experiments (i.e. not through the ice layer) was that dipping depths of the receiving unit and the laser beam were different. Such schemes of communication arrangement are called noncoplanar. The optical axes of the radiator and the receiving system were parallel to the lower border of the ice, did not cross each other, and the distance between them was 20 cm. The average radiant power of the laser on the first mirror did not exceed 4 W.

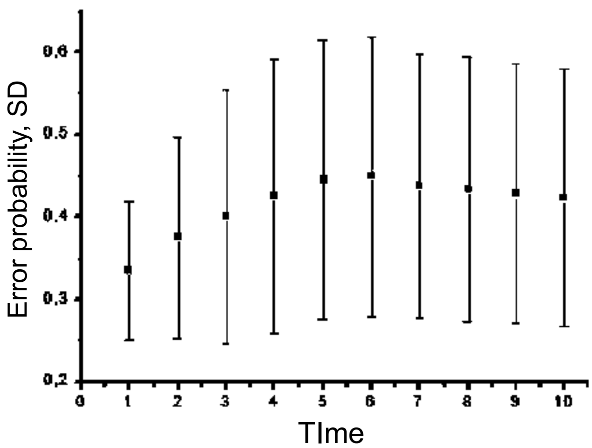

Fig. 3. Dependencies of single values of error probability and SD intervals (vertical lines) on the period of underwater channel quality probing (for communication conditions, see the text)

Let us describe the results of summer (May) tests of the same year, which were conducted using the same laboratory set and scheme of communication channel arrangement as in February (Fig. 1) but with laser radiant power of 6 W. The receiving unit and the laser source were dipped at a depth of 1 m from the water surface. The photo (Fig. 2) shows the main units of the OECS laboratory set and the participants of the experiments. One of the main goals of these experiments was to determine the maximum *L* with fixed characteristics and parameters of the radiator and the receiving unit. In the course of the experiments, for each value *L*, the angle α was fixed and the angle θ was changed (Fig. 1, *b*). Probability of communication errors and their SD were estimated in real time. 7,000 to 90,000 symbols were transmitted during each communication session with a duration varying between 7 to 30 min. The duration of each experiment was 1 to 3 h. *L* was increased with the step of 5 m starting from 5 m. Maximum *L* was equal to 40 m. This result is close to that previously obtained in artificial and natural water basins [11].

Fig. 3 shows one of the results of quality probing of the underwater channel with *L* = 40 m. Quality criteria: sample average and SD of communication errors (y-axis in Fig. 3) and conditioned time (x-axis). The values of angles α and β (Fig. 1, *b*) were 8.5 and 75.0° respectively.

Unlike the results obtained in winter (February), with *L* = 25 m [12] and close to the said values of α and β, the quality of the summer (May) communication channel was significantly worse than that of the winter one. This may be explained by the fact that

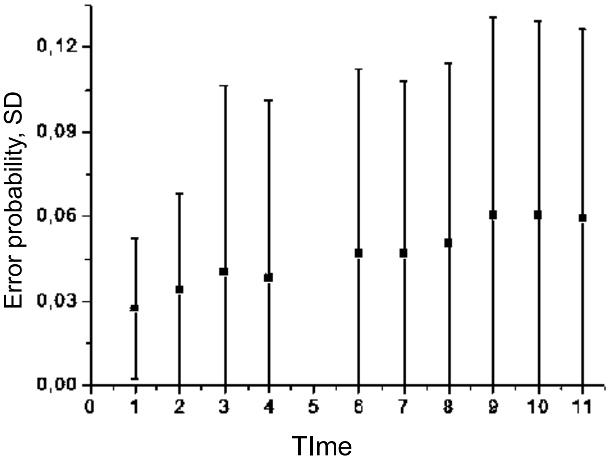

Fig. 4. Similar to Fig. 3. The "blue" laser and the receiver are in the water on the level of 10 cm from the lower border of ice. L = 10 m, α = 3°, and β = 2°

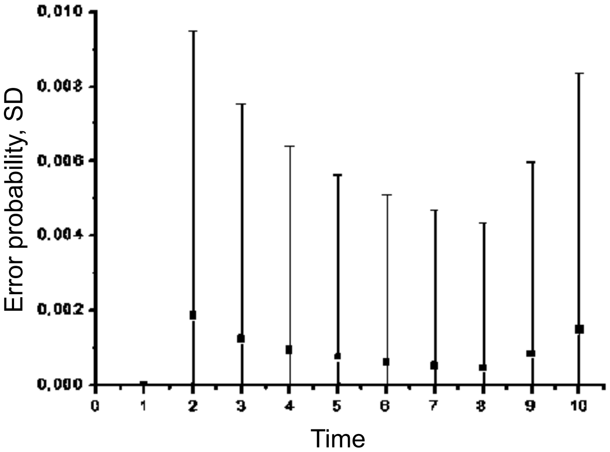

Fig. 5. Similar to Fig. 3 and 4. The "blue" laser and the receiver are in the water on the level of 43 cm from the lower border of ice. L = 10 m, α = 31°, and β = 25°

increasing of L causes decreasing of fluence on the entry gap of the receiving system which is not compensated by increasing of laser radiant power from 4 to 6 W in these experiments. Another reason of deterioration of quality of the underwater communication channel is that water turbidity is higher in summer than in winter when the water basin is covered with ice and is not being filled with substances increasing its turbidity (see, for instance, [16, 17]).

In 2018, the laboratory setting of the bistatic OECS was modified: FEU-84 was replaced by UFK-4G-2 photomultiplier (manufactured by OOO Katod, Novosibirsk), the optical unit of the receiving system was supplemented by *Semrock FF01–442/42–25* filter, and a semiconductor laser on the basis of the *B2000* module was used as a radiator with the average impulse mode power of 20 mW (peak λ = 445.0 nm). In February 2018, using this (modified) OECS set, the experiments similar to those conducted in 2015 using the "blue" laser were conducted with the average power of 13 mW and the same value of L (Fig. 1). Let us compare the quality of underwater bistatic communication channels for two variants of receiving systems. The example of the estimation results of probabilities and SD of communication errors in the "blue" underwater winter channel taken from [12] is shown in Fig. 4.

Fig. 5 shows one of the quality estimation results of the "blue" underwater bistatic OECS channel during the experiments in February 2018. As we can see, the quality of the 2018 "blue" channel is an order of magnitude higher than that of the 2015 one. If we check the geometrical characteristics of the communication channel formation schemes, we can see that they were more optimal in 2018 than in 2015. In the first case, the angles α and β complied with the situation when the receiver was oriented towards the source; in the second case, the receiver was oriented towards the section of the laser beam distant from the source. The average laser ra-

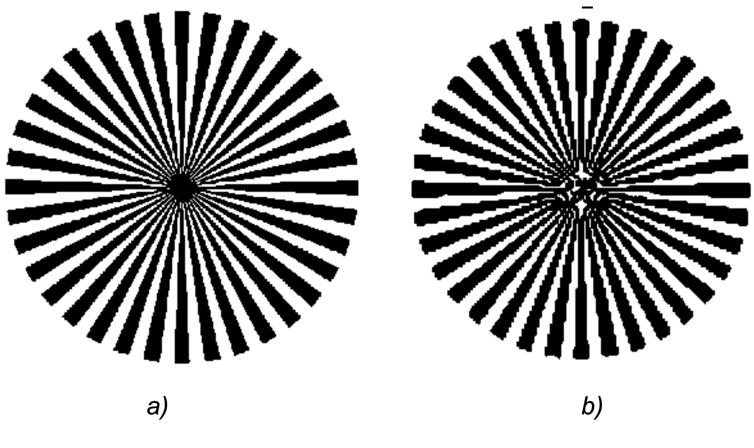

Fig. 6. Original sectorial target (*a*) and received image of the same (*b*)

diant power is 1.5 times higher in the second case than in the first one, but does not provide an increase of the communication channel quality by an order of magnitude. Therefore, the communication quality significantly increased in 2018 due to application of UFK-4G-2 photomultiplier.

In 2018, experimental transfers of images of a flat test object (sectorial target) were conducted. Fig. 6 contains the images of this object for communication conditions compliant with Fig. 5.

3. CONCLUSION

Possibility to develop operational optoelectronic systems of bistatic underwater communication based on scattered laser radiation in the visible range of wavelengths in lake water with base distances between the source and the receiver L of up to 40 m was experimentally confirmed, which is consistent with the results of [11].

There are reasons to propose that the range of coverage of such OECSs may reach hundreds of metres by applying laser sources with significantly higher output and more sensitive photodetectors. We also proved that the application of contemporary UFK-4G-2 photomultipliers instead of FEU-84 increases the quality of communication by an order of magnitude.

ACKNOWLEDGEMENT

The work was conducted with financial assistance within the framework of the Priority Area II.10, project II.10.3.3 “Direct and Reverse Problems of Sounding of Atmosphere and Earth Surface, Atmospheric Correction and Optoelectronic Communication Systems Based on Scattered Laser Radiation”.

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Light & Engineering
Vol. 27, No. 5, pp. 103–111, 2019
https://doi.org/10.33383/2018-100

ESTIMATION OF MEASUREMENT ERROR OF THE SEAWATER BEAM ATTENUATION COEFFICIENT IN TURBID WATER OF ARCTIC SEAS

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ABSTRACT

The article describes the estimation of measurement error of seawater beam attenuation coefficient using the Monte Carlo method. Measurements of the beam attenuation coefficient and its vertical distribution are the most common type of hydro-optical investigations since it is widely used for the research of light distribution in sea medium. Moreover, the beam attenuation coefficient is closely related to the concentration of the suspended substance and may be used for its estimation. Usually, the measurements of beam attenuation coefficient are conducted with small instrument base in rather transparent waters. In this case, the method errors of the beam attenuation coefficient measurement are low. However, in practice, cases of very turbid waters (near-bottom nepheloid layers), where measurement errors of beam attenuation coefficient significantly increase due to multiple scattering within the instrument base, are often encountered. The estimation of such errors is reviewed in this work. The effect of scattering phase function on the considered errors is described to the greatest extent. Moreover, the effect of the instrument base length and angle of view of the receiving system on measurement errors of beam attenuation coefficient is studied. Corresponding estimations are provided.

Keywords: beam attenuation coefficient, nepheloid layers, Monte Carlo method, measurement error, Bouguer law, multiple scattering

1. INTRODUCTION

Nowadays, the measurements of the beam attenuation coefficient c and its vertical distribution are the most widely used type of hydro-optical investigations. The value of the beam attenuation coefficient (alongside with other hydro-optical indicators) significantly affects the solar radiation (and radiation of artificial light sources) distribution in a water medium.

Numerous investigations have shown that the value of the beam attenuation coefficient is closely related to the concentration of the suspended substance and may be used for its estimation [1, 2]. It needs to be noted here that hydro-optical measurements have a particular advantage since they are conducted continuously in space and time, whereas geological methods are very time-consuming.

It should be noted that recently the measurements of beam attenuation coefficient are being widely used for the research of different biogeochemical processes in the ocean (among the recent publications, see, e.g. [3–5]).

The measurement method of beam attenuation coefficient is based on the Bouguer law $P = P_0 e^{-cL}$, where P_0 and P are the values of radiant flux before and after the light passes the distance L in the water, c is the value of beam attenuation coefficient. For correct determination of c, it is necessary that the light beam coming out of the instrument had a low divergence and the receiving system had a low angle of view. In the rather transparent waters, the value of $\tau = cL$ is relatively low, but there are situations when it is essentially higher than one (e.g. in turbid waters in areas of river runoffs or in near-bottom nepheloid layers), and the multiple scattering of light along the beam axis is necessary to be taken into account in this case. This goal is the main subject of this work. It should be noted that the Monte Carlo method is applied for estimation of measurement error of beam attenuation coefficient for the first time.

2. PUM TRANSPARENCY METER. OPTICAL SCHEMATIC AND ADVANTAGES OF THE INSTRUMENT

Fig. 1 shows the optical schematic of the PUM transparency meter (universal small-size transparency meter) which is being used for field experiments of the Shirshov Institute of Oceanology, Russian Academy of Sciences recently [6].

The instrument is based on the classical two-channel optical arrangement with one light source and one photodetector, the reference channel is located inside the body. The main advantage of the two-channel arrangement is the elimination of non-stabilities of the light source and the photodetector in the course of measurement signal level setting on the basis of the reference one (which is required for calculation of beam attenuation coefficient).

In the measurement channel, the light source 1, which is a high-output LED, sends a light beam to the studied medium (seawater) through semi-transparent mirror 10, collimator 6, and illuminator 7. The beam reflected by cube-corner reflector 8 gets inside the instrument again through the illuminator 7, passes the lens 6 and, being reflected by the semi-transparent mirror 10, gets into the photodetector 2. In the reference channel, the light beam gets on the spherical mirror 3 through the semi-transparent mirror 10 and, being reflected by the former, through the same semi-transparent mirror, it gets to the photodetector, at output of which there is the interference filter 11 passing the radiation with light source wavelength (532 nm) and half-width of 20 nm.

For calculation of beam attenuation coefficient, two additional channels are used. The dark signal channel is required for calculation of background signal with the light source switched off and is used for compensation of the temperature drift of the photodetector (the background signal is subtracted from the reference signal). The reference channel is used for calculation of the background signal (the reference signal) from the light scattered by the water which gets into the measurement channel. The reference signal is measured with the light source switched off and is subtracted from the signal of the measurement channel. For additional reduction of external light, the narrow-band interference filter 11 with the same spectral characteristics as those of the light source is used. Formation and sequence of light fluxes to the input of the photodetector 2 are provided by the optical modulator 4 installed along the axis of the electric drive 5. Apart from closing the optical fluxes, the modulator forms synchronised impulses controlling switching on of the light source 1 and allowing to separate the components corresponding with light fluxes of each of the four channels out of the impulse signal in the photodetector output.

In the course of operation, the PUM transparency meter has undergone numerous retrofits. In particular, apart from the standard installation place of the cube-corner reflector at a distance of $L/2$ = 30 cm from the illuminator, installation of the cube-corner reflector is provided at a distance of $L/2$ = 5 cm for measurements in very turbid waters.

Main optical parameters of the PUM transparency meter are shown in Table 1.

Table 1. PUM Transparency Meter Parameters

Parameter	Value
Beam divergence	$2 \cdot \theta_0 = 12'$ (in water)
Receiver view angle	$2 \cdot \theta = 20'$
Beam width	$2w$=20 mm
Short base	L=10 cm
Long base	L= 60 cm
Collimator diameter	$2 \cdot R$ = 35 mm

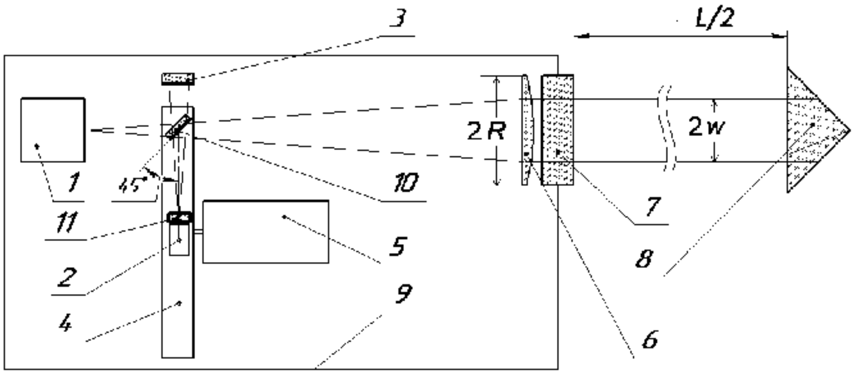

Fig. 1 Optical schematic of PUM transparency meter: 1 – light source; 2 – photodetector; 3 – spherical mirror; 4 – optical modulator; 5 – electric drive; 6 – collimator; 7 – illuminator; 8 – cube-corner reflector; 9 – sealed case of the instrument; 10 – semi-transparent mirror; 11 – interference filter

3. VERTICAL PROFILES MEASUREMENTS EXAMPLES OF BEAM ATTENUATION COEFFICIENT IN HIGH-TURBID WATERS

The measurements described below were conducted during the 69th expedition of the Research Vessel "Akademik Mstislav Keldysh" in 2017. The area of research was a wide one: from the Barents Sea to the East Siberian Sea.

The distribution of beam attenuation coefficient in the researched waters has high spatial-temporal variability. In this area, both waters with the value of *c* close to that of transparent ocean waters and high-turbid waters with the value of $\tau = c \times L$ essentially exceeding one are encountered. The locations of stations where anomalously high values of *c* ($c >$ 10 m^{-1}) are shown in Fig. 2.

Usually, such waters are encountered in near-bottom layers (the so-called near-bottom nepheloid layers caused by spreading of bottom sediments). In the Khatanga river mouth, the water is anomalously turbid ($c >$ 40 m^{-1}) from the surface to the bottom. The examples of the results of measurements conducted in such waters are shown in Fig. 3.

Fig. 3 shows that all the graphs have near-bottom nepheloid layers, where the values of beam attenuation coefficient *c* exceed 20 m^{-1} (in some cases, the value of *c* exceeded 50 m^{-1}). It is obvious that multiple scattering of light along the base

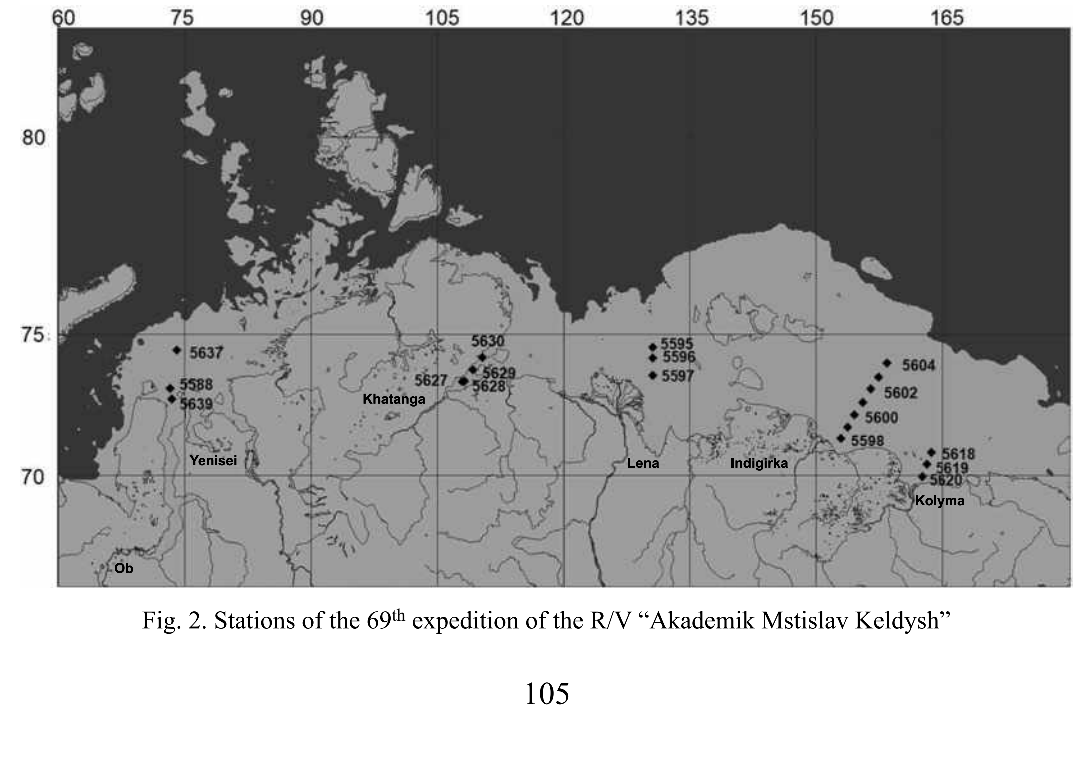

Fig. 2. Stations of the 69th expedition of the R/V "Akademik Mstislav Keldysh"

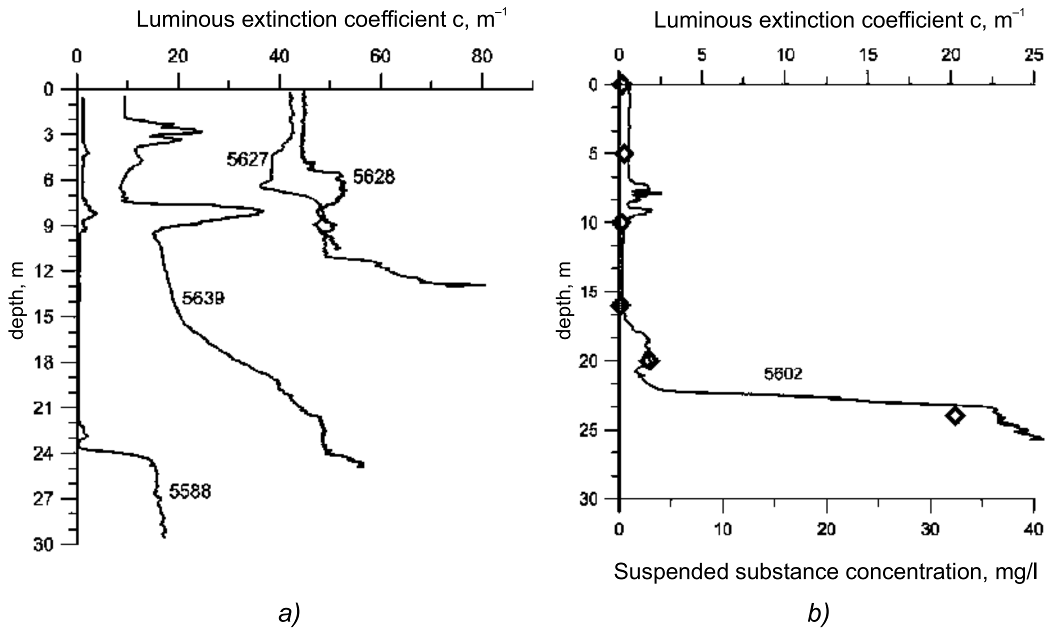

Fig. 3. Examples of Measurements of vertical profiles of beam attenuation coefficient in high-turbid waters. Station numbers are given in the graphs. a – st. 5627 and 5628 – Khatanga river mouth, st. 5588 and 5639 – Kara Sea; b – st. 5602 – East Siberian Sea in the area of the Indigirka river mouth. Diamonds indicate the suspended substance concentration. Thick near bottom nepheloid layer is well seen

length L should be taken into consideration for such layers. In all cases when the value of τ exceeded 9, the sensitivity of an instrument with long base was not sufficient, whereas the measurements with short base gave satisfactory results (Fig. 3).

The measurements of the vertical distribution of beam attenuation coefficient in near-bottom layers are well-confirmed by direct measurements of suspended substance concentration. The corresponding example is shown in Fig. 3b.

4. APPLICATION OF THE MONTE CARLO METHOD FOR ESTIMATION OF MEASUREMENT ERROR OF BEAM ATTENUATION COEFFICIENT

As a parameter of error estimation, the value $\delta c = c - c_{meas}$, where $c_{meas} = \ln(P_0/P)/L$ was selected. In [7], the problem of spreading of a narrow light beam, which essentially resolves itself into calculation of the value of P depending the parameters R, L, and optical properties of medium was considered. However, it is worth noting the difference between the setup of the problem and our case: the distribution of irradiance was studied at some distance from the source, i.e. the view angle of the receiver θ was equal to 90°, whereas in our case, θ = 10' and, as it will be explained below, this difference is quite essential.

The beam attenuation coefficient c measurement error caused by scattered light detection by the detector was calculated using the Monte Carlo method. The simplest variant of this method was used: direct modelling of photon trajectories [8, 9]. For each photon, the processes of absorption and scattering in medium, reflection from the cube-corner reflector, and return to the illuminator were modelled. Only those photons, for which the incidence angle did not exceed the value of θ, were taken into account.

First, let us consider the dependence of the calculation parameters on scattering phase function. Unlike the problems of remote sensing, in which the results are mostly defined by the behaviour of the phase function in the backward hemisphere, here the scattering at low angles of about 1° is the most essential factor which defines entry of the scattered light to the photodetector. Dependence of the results of calculations on scattering phase function, unlike other parameters considered below, which are known in advance or set a priori, is the most uncertain one. It is possible to use only reference data here.

The experimental data regarding scattering phase functions measured in the Indian Ocean at depths lower than 100 m and exceeding 100 m is contained in the Ocean Optics monograph, volume 1, part II,

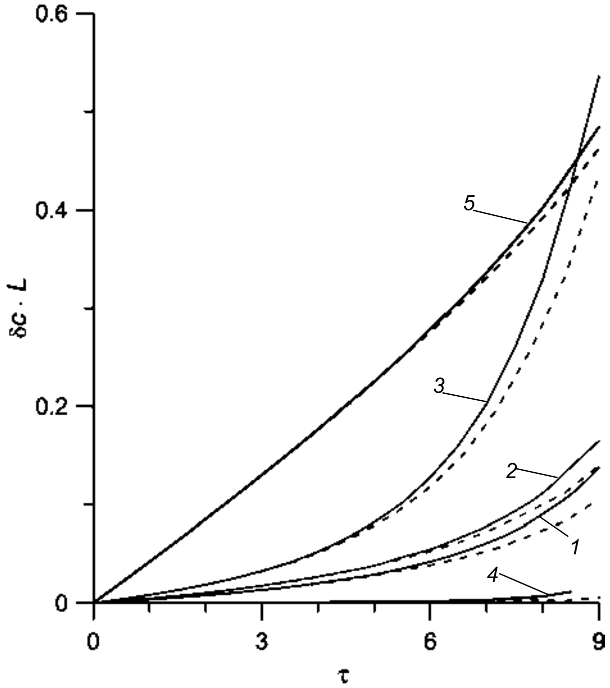

Fig. 4. Dependencies $\delta c{\cdot}L$ on optical thickness for different indicatrices: 1 − *ind1*, 2 − *ind2*; 3 − *Kl*, 4 − *Ks*, 5 − *Petzold*. Continuous lines − short base (0.1 m), dashed lines − long base (0.6 m)

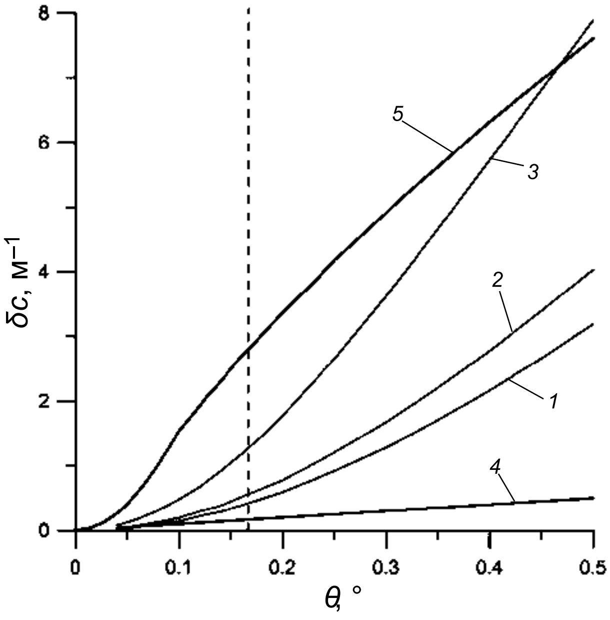

Fig. 5. Dependencies of δc on the receiver angle of view θ for different indicatrices: 1 − *ind1*, 2 − *ind2*; 3 − *Kl*, 4 − *Ks*, 5 − *Petzold*. Vertical dashed line indicates the value of the θ parameter for PUM

chapter 7 [10]. Below we will indicate these phase functions as *ind*1 and *ind*2 respectively.

Table 8.6 of the same monograph contains phase functions for pure water and for fine and coarse suspended substances. For coarse size (biogenic substance), the range of particle sizes was taken in the form of Junge distribution r^{-v}, where v =3. Refractive index of particles is equal to 1.03. For fine substance (terrigenous substance), complex distribution within the range of particle sizes from 0.01 to 1.3 mm was taken. In this case, the refractive index of particles is equal to 1.15. We will indicate scattering phase functions for coarse and fine fractions as *Kl* and *Ks* respectively.

In [11], the results of measurement of scattering phase function in coastal waters (San Diego bay) and in the waters of the open ocean within the range of angles from 0.1 to 175° are listed. This data is reproduced in [12] and at http://www.oceanopticsbook.info/view/references/publications.

If we presume that the only essential parameter with length dimension in this problem is the baseline length L, for the given phase function, the nondimensional value $\delta c{\cdot}L$ depends only on the nondimensional parameter $\tau = c{\cdot}L$. The graph of such dependence is shown in Fig. 4. It can be seen that, with relatively high values of the parameter τ, for some phase functions, for instance, for *Kl*, this presumption is not met: with the same value of the parameter τ, the value of $\delta c{\cdot}L$ for long base is less than for the short one. It is caused by the fact that, apart from L, there are other parameters with length dimension in the problem, in particular, the radius of the collimator R. Dependence of δc on R is essential with $R < L{\cdot}\tan\psi$, where ψ is the divergence angle of the photon beam with incidence angle less than the view angle of the receiver θ. The value of angle ψ essentially depends on the scattering phase function: the more the phase function is elongated forward, the less this angle is. With a short base, the condition $R > L{\cdot}\tan\psi$ is met for all phase functions, whereas with long base, it is not always so.

Dependencies of δc on the view angle of the receiver for different phase functions are shown in Fig. 5. For PUM, this angle equals to 0.167°. This dependence itself is rather obvious: the more the receiver view angle is as compared to the beam divergence, the higher is the effect of scattered light and the higher is the beam attenuation coefficient measurement error.

The conducted calculations show that changes in the value of beam divergence slightly affect the value of c measurement error (naturally if the beam divergence is significantly less than the receiver view angle). Moreover, the calculations show that changing the beam width slightly affects the results

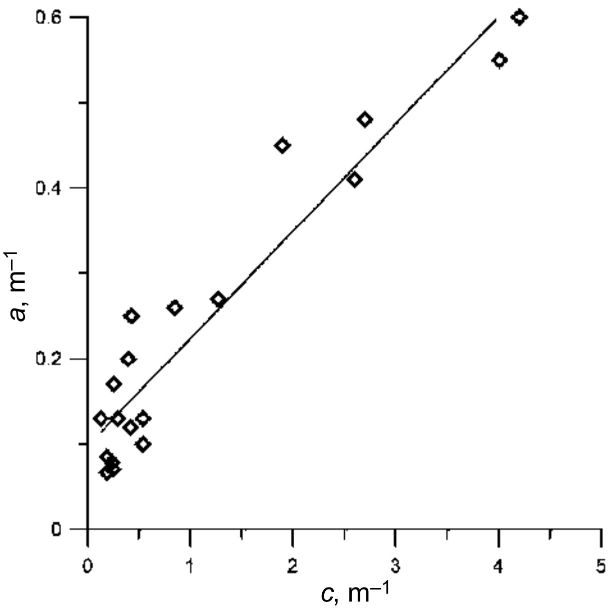

Fig. 6. Relation between the parameters of absorption and extinction in the Barents Sea (1998)

(if it is significantly less than the diameter of the illuminator).

It should be noted that the value of absorption, naturally, does not affect deviation from the Bouguer law. Its increase causes only a decrease of the relative measurement error of the beam attenuation coefficient.

5. ESTIMATION OF MEASUREMENT ERRORS OF THE BEAM ATTENUATION COEFFICIENT IN THE SURFACE LAYERS OF ARCTIC SEAS

Above, rather essential effect of scattering phase function in the low angles range on the beam attenuation coefficient was demonstrated. Below, we will consider the possibility of determination of the error of beam attenuation coefficient in the surface layer with scattering phase function taken into account. This possibility is based on the close relation between the backscattering coefficient

$$\int_{\frac{\pi}{2}}^{\pi} p(\gamma)\sin\gamma d\gamma \quad b_b = 2\pi \int_{\pi/2}^{\pi} \beta(\gamma)\sin(\gamma)d\gamma ,$$

where $\beta(\gamma)$ is the volume scattering function of sea water, and sub-surface radiance reflectance

$$\rho = \pi \cdot L_u/E_d,$$

where L_u is the sub-surface upwelling radiance, E_d is the sub-surface downwelling irradiance. The radiance reflectance ρ can be measured both by contact and remote (using satellite colour scanners) methods.

A simple and, at the same time, rather exact expression describing the dependence of the radiance reflectance on inherent optical properties is given in [13]: $\rho = 0.0922 \cdot \pi \cdot b_b/a$, where a is the absorption coefficient of sea water, from which:

$$b_b = 3.45\rho a . \quad (1)$$

The relation between the absorption coefficient a and extinction coefficient c is acquired based on the results of measurements conducted in the Barents Sea in 1998 (the measurements were conducted both in turbid waters of Pechora Sea and in relatively transparent waters of the Western part of Barents Sea). At that time, diffuse attenuation coefficient K_d at a wavelength of 530 nm and the beam attenuation coefficient c were measured at the same time. According to [14], the relation between a and K_d is written as $K_d = D_0(\theta)\cdot k_1 \cdot (a + b_b)$. Given that the measurements were conducted with the Sun zenith angle of about 60°, for approximate calculations, $D_0(\theta)\cdot k_1 = 1.3$ may be taken (see [14, table 4]). From here the value of $a(530)$ is determined (the value of b_b may be estimated based on the approximate formula $b_b = 0.018 \cdot c/b$, where b is the seawater scattering coefficient [15]). The graph of dependence of the absorption coefficient on the extinction coefficient based on the measurements conducted in the Barents Sea in 1998 is given in Fig. 6. It can be seen that there is a rather close correlation between the considered parameters (determination coefficient $r^2 = 0.9$). The corresponding regression equation is written as a (530) = 0.0983· c (530) + 0.05, from which, with consideration of (1), we obtain:

$$b = 0.902c - 0.05, b_b = \rho\left(0.335c + 0.252\right). \quad (2)$$

For estimation of the scattering phase function, the two-parameter model of light-scattering properties of sea water [16] was used; in accordance with it, volume scattering function $\beta(\gamma)$ may be presented as the sum of contributions by pure sea water $\beta_w(\gamma)$ and fine and coarse suspended substances ($v_f \cdot \beta_f(\gamma)$ and $v_c \cdot \beta_c(\gamma)$ respectively):

$$\beta(\gamma) = \beta_w(\gamma) + v_f\beta_f(\gamma) + v_c\beta_c(\gamma), \quad (3)$$

where v_f and v_c are volume concentrations of fine and coarse suspended substances respectively; the tables of functions $\beta_w(\gamma)$, $\beta_f(\gamma)$, and $\beta_c(\gamma)$ for a wavelength of 550 nm are given in [10]. For re-calculation to the operating wavelength of the transparency meter, we use the spectral dependence formulas: $\beta_w \sim \lambda^{-4,3}$, $\beta_f \sim \lambda^{-1,7}$, $\beta_c \sim \lambda^{-0,3}$.

To define the parameters of the model v_f and v_c, first, we integrate (3) over the whole sphere, then over the backward hemisphere. As a result, we obtain a pair of linear equations in two variables:

$$b=b_w+v_f b_f+v_c b_c;\ b_b=\tfrac{1}{2}b_w+v_f b_{bf}+v_c b_{bc}, \qquad (4)$$

where b_w is the scattering coefficient of pure sea water,

$$b_{f,c}=2\pi\int_0^{\pi}\beta_{f,c}(\gamma)\sin(\gamma)d\gamma,$$

$$b_{b_{f,c}}=2\pi\int_{\pi/2}^{\pi}\beta_{f,c}(\gamma)\sin(\gamma)d\gamma.$$

Solving the equations (4) with consideration of (1) and (2), applying the parameters v_f *and* v_c to (3), and multiplying the result by the normalization factor $1/b$, we obtain the scattering phase function, and therefore, all parameters required for calculation using the Monte Carlo method.

In Fig. 7, the estimation results of the dependence of the extinction coefficient measurement error caused by multiple scattering on radiance reflectance for different values of L and c are shown. Like in Fig. 4, the difference of the values of the non-dimensional value $\delta c{\cdot}L$ for similar values of τ but different values of L is caused by the fact that, with long base, the value $L\cdot\tan\psi$ (ψ is the angle of light beam divergence) exceeds the collimator radius.

Estimation of the measurement error of the extinction coefficient c using the parameter ρ is possible only for surface layers. Possible values of the parameter ρ for this region may be evaluated based on satellite data or data of contact measurements, e.g. by means of a floating spectroradiometer [17]. During the 69th cruise of the R/V "Akademik Mstislav Keldysh", the highly turbid surface layers we were interested in were found at stations 5627 and 5628 in the Khatanga river mouth (Fig. 2, 3). Shipboard measurements of ρ were not conducted at these stations. The estimation capability of this parameter by means of satellite data is considered below.

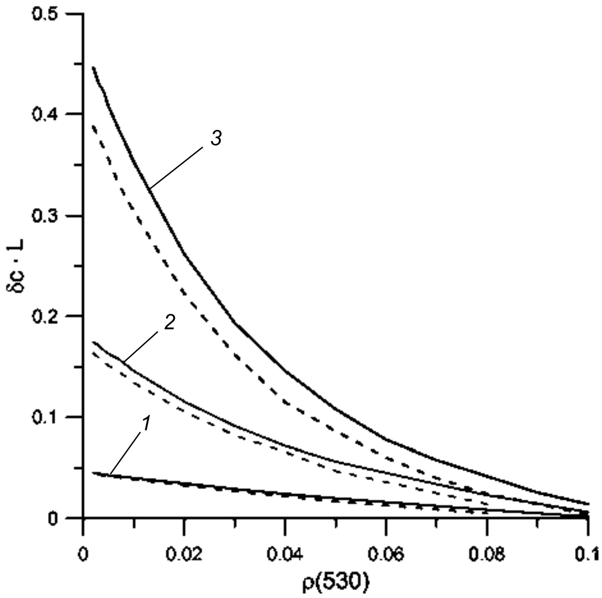

Fig. 7. Dependence of measurement error of the luminous extinction coefficient caused by multiple scattering on luminance factor of water medium: 1 – τ = 3; 2 – τ = 6; 3 – τ = 8. Continuous lines – L = 0.1 m, dashed lines – L = 0.6 m

The data files of the *MODIS Aqua* and *MODIS Terra* satellite ocean colour scanners contain the parameter $R_{rs}(\lambda) = L_u^+/E_d^+$ (L_u^+ is the water-leaving radiance, E_d^+ is the downward irradiance above the surface) for a wavelength of λ = 531 nm. The value ρ can be with a good accuracy calculated using the formula $\rho(\lambda) = R_{rs}(\lambda)/(0.495{\cdot}R_{rs}(\lambda) + 0.165)$ [18]. There are no data exactly referenced to coordinates and measurement time of stations 5627 and 5628, however, it can be proposed that the required value of ρ lies within the interval between the minimal and the maximum values of it for this region within a month. Based on the *MODIS Aqua* data, average values of ρ for each day of August, 2017 were calculated within the inner part of the contour bounding the Khatanga river mouth (in September, the data for this region was not available due to overcast conditions). Average value was equal to 0.044, maximum value was equal to 0.069, and minimal one was equal to 0.017. From the data shown in Fig. 7 follows that, in case of using a short base L=0.1 m with minimal value of ρ, the relative measurement error of the extinction coefficient is 4 % for c = 80 m^{-1} and 2 % for c = 20 m^{-1}.

CONCLUSION

The value of scattering phase function rather essentially affects the measurement error of the extinction coefficient (the more the phase function is prolonged, the higher is the error). Note that it relates to scattering at angles of about 1°. During measurements in surface layers, for estimation of the scattering phase function, the value of radiance reflectance at a wavelength of 530 nm ρ (530) may be used. In this case, the measurement error of c is low when the contribution of the coarse suspended substance in scattering at small angles is insignificant (the values of ρ (530) are rather high). In case, when the coarse suspended substance prevails in small-angle scattering, the considered error significantly rises (the values of ρ (530) are rather low). During measurement of the extinction coefficient in deep layers (in particular, in the near-bottom nepheloid layer), naturally, there are no phase function data, and the data given in [10] should be used for estimation of the measurement error of the extinction coefficient.

The instrument base length significantly affects the measurement error of c with high optical thicknesses of $\tau = c \cdot L$ (up to a few tens of a percent). Therefore, for measurement of the extinction coefficient in turbid waters, it is necessary to use short base for which the measurement errors of c caused by multiple scattering along the base length are significantly lowered.

The conducted calculations show that the receiver view angle significantly affects the measurement error of c. Therefore, it is necessary to use instruments with beam divergence significantly lower than the view angle of the receiver. Moreover, the calculations show that changing of the beam width slightly affects the results (naturally, if the beam radius is significantly less than the radius of the input hole of the receiver).

The results of measurements described herein and the conducted calculations confirm that the PUM transparency meter with short base may be recommended for measurement of the beam attenuation coefficient in highly turbid waters.

ACKNOWLEDGMENT

This research was performed in the framework of the state assignment of Minobrnauki RF (theme No.0149–2019–0003). The authors are grateful to O.V. Kopelevich for attention to the work and valuable comments. The authors thank M.D. Kravchishina for provided suspended substance concentration data.

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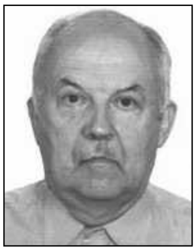

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Light & Engineering
Vol. 27, No. 5, pp. 112–116, 2019
https://doi.org/10.33383/2018-013

APPLICATION OF HIGH-BRIGHTNESS LEDS FOR SIMULTANEOUS MEASUREMENT OF RADIATION SCATTERING AND FLUORESCENCE CHARACTERISTICS IN SEA WATER

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ABSTRACT

The studies of radiation scattering and fluorescence in sea environment are required for more precise description of radiation behaviour in the upper layers of ocean and diagnostics of environmental condition of seawaters. Application of high-brightness LEDs allowed us to develop a unique method and device for studying of scattering properties and fluorescence of natural waters. Brief descriptions of the device (nephelometer) design and the results of its testing are given. The main advantage of the proposed method is controlled accountancy of the effect of coherent scattering on the results of measurements. Measurements of characteristics of all types of scattering are made by means of one device and using one sample.

Keywords: high-brightness LEDs, nephelometer, radiation scattering by water, fluorescence of natural waters

1. INTRODUCTION

The studies of hydro-optical properties of seawater conducted by the Marine Hydrophysical Institute of the Russian Academy of Science in recent years discovered the imperative necessity of application of new approaches to measurements of radiation scattering indicatrix for explanation of the reasons of incompliance of the clean waters molecular scattering theory with the data of field measurements [1, 2]. The radiation scattering indicatrix data allows us to find such characteristics of suspended material as particle size distribution, to divide it in coarse and fine fraction [3], to find the particles refractive index [4], dependence between the scattering properties of microparticles and their size [5], and to determine the total concentration of suspended material without dividing it into mineral and organic components [6]. Despite the fact that knowledge of the scattering indicatrix has such high relevance for ocean optics, there were not many field measurements of indicatrix due to complexity of designing of equipment for such measurements. The main challenge is that measurement of scattering indicatrix within the whole range of scattering angles requires such radiation sources (RS) which have both very small dimensions of luminous object and very high luminous efficacy. Some high-brightness LEDs, which have appeared over the recent years, not only optimally combine these contradictive requirements but also allow us to select required spectral areas within the range of (350–780) nm.

2. NEW APPROACH TO MEASUREMENTS OF RADIATION SCATTERING ANGULAR FUNCTION AND FLUORESCENCE

The successes in development of semi-conductor radiation sources allow applying tungsten halogen lamps (THL) as RSs in spectral hydrooptical devices to stop. The luminous efficacy of contemporary high-brightness LEDs is higher than that of THLs. Calculations show that application of LED

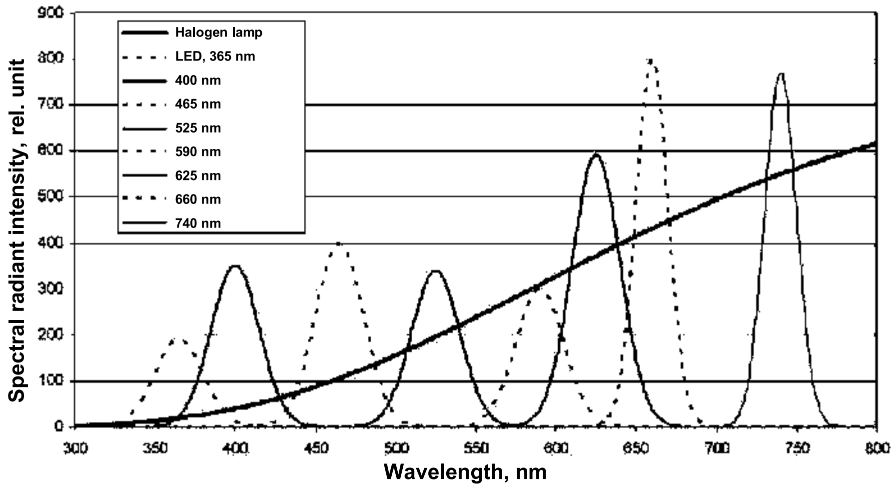

Fig. 1 Relative radiation spectra of LED and THL with correlated colour temperature of 2900K

as RS instead of THL provides ten times higher radiant flux within the same spectral bands and even hundreds of times higher in the short-wavelength region of the spectrum [7]. The LED radiation spectra are relatively narrow (15–35) nm, therefore it is accepted to consider their radiation quasi-monochromatic. Our preliminary evaluation showed that radiance of LEDs is a hundredfold higher than that of the previously used 12W THL. With peak radiation wavelength λ_p decreasing the advantages of LEDs as compared to THL are increasing (Fig. 1).

Application of high-brightness LEDs as RS allowed us to develop a unique method and a device for studying of scattering properties and fluorescence of natural waters. We conducted modernisation of an unique polar nephelometer which allowed significantly to widen its functionality and to provide capability not only to measure scattering indicatrix within the whole range of scattering angles but also fluorescence of different types of phytoplankton cells and dissolved organic matter [7]. The new multi-purpose polar nephelometer for the newest studies of radiation scattering and fluorescence is a third-generation radiation scattering measurement device, which performs angular scan using the periscope operation principle by means of rotation of special glass prism around the axis of photodetector.

As a result of application of high-brightness LEDs as RS, the advanced polar nephelometer achieved a capability to register the signal of non-coherent scattering. For this purpose, the nephelometer radiation unit was supplemented by a special LED changing mechanism and the photodetector unit was supplemented by a computer-controlled filter changing mechanism. If the radiation and transmission spectra are located in one spectral region, the ordinary coherent scattering is measuring, and if they are located in different regions, fluorescence and the Raman scattering are defineding. Availability and the level of ambient illumination are controlled using the angular structure of the measured signal. The new device uses the high design technology and contemporary electronic components. The functional diagram of the device for measurement of volume scattering and fluorescence of different types of phytoplankton cells and dissolved organic matter is shown in Fig. 2.

For the first time in the world practice, this version of nephelometer uses a set of 8 high-brightness

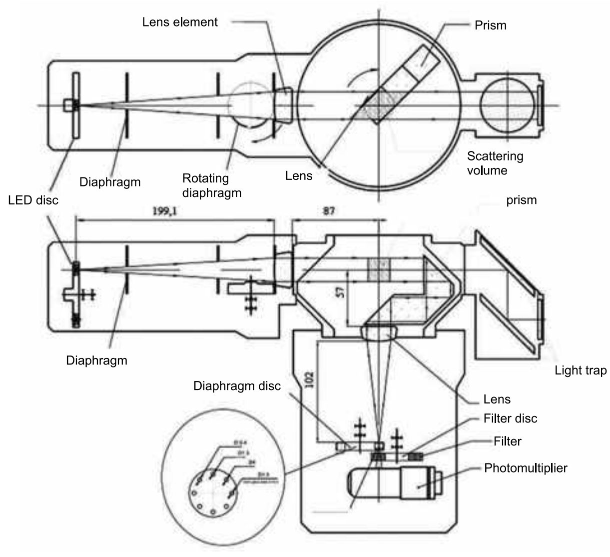

Fig. 2. Principal scheme of measurements of scattering characteristics with the new nephelometer

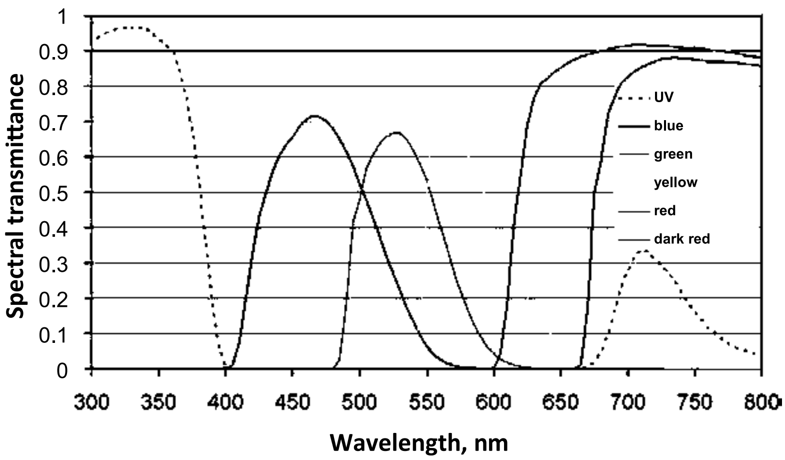

Fig. 3. Relative transmission spectra of filters

narrow-band various-spectrum LEDs with λ_p = 365, 400, 465, 525, 590, 625, 660 and 740 nm and radiation bandwidth from 10 to 20 nm [7]. The LEDs are installed around a circumference over each 45° on a rotational disc, which is a radiator designed as a cylinder with inclined cooling fins. Changing of LEDs is performed using a step engine which turns the radiator with filter for the set angle by a microprocessor signal. Power supply of LEDs is performed by supplying voltage to two spring brushes sliding on the disc collector with eight contact sectors connected with corresponding LEDs which rotates together with the radiator.

These LEDs radiate significantly more than THL, which significantly lowers the random noise of the photomultiplier during measurement of small radiant flux in the region of large scattering angles and low levels of fluorescent glow. The dimensions of the LED luminous object, which are significantly less than those of THL, allow RS beam divergence to decrease and, therefore, to increase angle resolution during measurements of radiation indicatrix. Another significant advantage of application of LEDs is longer service life of RSs based on them. The guaranteed service life of LEDs is 100,000 hours and more, which allows us to use them in optical devices within the whole period of their persistent operation. It is also well-known that changing of a burned-out THL is associated with time-consuming adjustment and calibration of a device, which sometimes lead to loss of data especially during field expeditions. One more advantage of application of LEDs is capability to control radiance and therefore radiance of scattered radiation by changing radiant intensity of LED. Moreover, it is application of high-brightness LEDs which allows us to use the same device for measurement of fluorescent properties of seawater.

To make a polar nephelometer measure both radiation scattering angular function and characteristics of seawater fluorescence, the light detector of the polarimeter should be equipped with a set of filters with transmission maximums adjusted in accordance with λ_p of LEDs. Various combinations of LED and filter pairs allow closely to register both a signal associated with coherent scattering and characteristics of fluorescence at one wavelength with exciting signal at another one. For this purpose, the light detector is supplemented with a set of corresponding filters made of coloured glass (Fig. 3).

Installation of filters opposite to the photomultiplier allows us to control the effects of non-coherent scattering and to measure the fluorescence characteristics.

The Table contains the measured values of the fraction of received coherent radiation and values of effective wavelength for all possible combinations of LEDs and filters in the device. The cells with bolded values should be considered as acceptable ones for measurement of coherent scattering by a combination of a LED and a filter. The combinations of LEDs and filters close to the diagonal of the fluorescence matrix allow to measure the values of coherent scattering. If the fraction of the latter is low, there is a capability in principle to measure the values of non-coherent scattering.

CONCLUSION

Application of contemporary high-brightness LEDs allowed us to develop a unique method and

Table. Calculated Values of Fraction of Received Coherent Radiation and Effective Wavelength

λ_p, nm \ Filter	UV	Blue	Green	Yellow	Red	Dark red
365	**0.88; 363 nm**	0.003; 418 nm	$<10^{-5}$	$<10^{-4}$	$<10^{-6}$	$<10^{-6}$
400	0.036; 390 nm	0.018; 412 nm	$<10^{-5}$	0.0001; 400 nm	$<10^{-6}$	$<10^{-6}$
465	$<10^{-6}$	**0.669; 465.1 nm**	0.0223; 496 nm	0.0001; 465 nm	$<10^{-6}$	$<10^{-6}$
525	$<10^{-6}$	**0.283; 516 nm**	**0.592; 525 nm**	0.0648; 554 nm	$<10^{-6}$	$<10^{-6}$
590	$<10^{-6}$	0.003; 565 nm	0.124; 578 nm	**0.51; 586 nm**	0.044; 617 nm	$<10^{-6}$
625	$<10^{-4}$	$<10^{-4}$	0.0106; 604 nm	**0.225 617 nm**	**0.56; 631 nm**	0.0006; 674 nm
660	0.026; 692 nm	$<10^{-6}$	0.0008; 616 nm	0.068; 642 nm	**0.851; 660 nm**	0.176; 685 nm
740	0.217; 732 nm	$<10^{-6}$	$<10^{-6}$	0.0008; 713 nm	**0.919; 739 nm**	**0.879; 739 nm**

a device for studying of scattering properties of natural waters.

The main advantage of the proposed method is controlled accountancy of the effect of coherent scattering. Measurements of characteristics of the two types of scattering are made by means of one device and using one sample.

Another advantage of the nephelometric method is a capability to conduct fluorometric measurements with sufficient approximation relative radiation spectra of RS and transmission spectra of detector filters.

ACKNOWLEDGMENT

The new method was developed under the RFBR project 16–05–00062 "The Research of Spectral Characteristics of Coherent and Non-Coherent Radiation Scattering in Sea Water".

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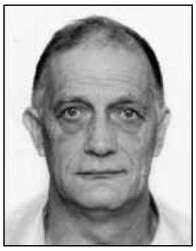

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Light & Engineering
Vol. 27, No. 5, pp. 117–121, 2019 *https://doi.org/10.33383/2019-009*

HIGHER EDUCATION WITH A SPECIALISATION IN LIGHT ENGINEERING AND LIGHT SOURCES AND TRANSFER TO FSES3^{++}

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ABSTRACT

The article describes the problems associated with previous Federal State Education Standards (FSES) in the Electronics and Nanoelectronics education speciality and education plans of the Light Engineering and Light Sources Bachelor's programme as well as education plans of the Theoretical and Applied Light Engineering Master's programme. Due to the adoption of FSES3^{++} and approval of professional educational standards, the light engineering community was offered to take part in the discussion of the issues of new education plans elaboration.

Keywords: FSES of higher education, the federal state educational standard of higher education, FSES of higher professional education, the federal state educational standard of higher professional education

The bachelors and masters in the area of light engineering are trained by NRU MEI, Kazan State Power Engineering University, N.P. Ogarev National State Research University of Mordovia (Saransk), Don State Technical University (Rostov-on-Don) and Saint-Petersburg State University of Film and Television.

The Light Engineering department of MPEI was established in 1933, it was the first such department established in the USSR.

In accordance with the orders of the Ministry of Education and Science of the Russian Federation [1, 2] under the common name of FSES3^{++}, the higher education institutions shall transfer to the education of students in accordance with these documents beginning from September 1, 2019.

Before discussing today's problems, let us remember the past. There were two specialities in the Light Engineering department of MPEI at the end of the 20th century: 1) Light Engineering and Light Sources; 2) Optoelectronic Devices and Systems. The selection of one of the three possible programmes (Electronics and Microelectronics, Electrical Engineering and Optical Engineering) within the scope of the second speciality was accompanied by serious discussions, and the first programme was selected for several reasons. The main one is related to the development of science and equipment and, therefore, many disciplines of the sub-division in the field of electronics. This mainly includes semi-conductor (LED) emitters, light control systems, control gears for discharge lamps, and LED control equipment a little later. Nowadays it is already difficult to imagine such disciplines of the sub-division as Light Devices, Designing and Technology of Manufacturing of Light Devices, Light Design Technologies, and Contemporary Problems of Electronics without LED light sources. The new programmes in these fields will appear and the existing ones will be developed by the new education plan. In the meantime, the second speciality was quite easily transformed into Quantum and Optical Electronics.

During the period from 2000 to 2010, the Ministry of Education of the Russian Federation also conducted education in accordance with the diplomat programme 645100 Electronics and Microelectronics, which included special disciplines, in particular, for the speciality 180600 Light Engineering and Light Sources alongside with the federal and national-regional (institution)-level disciplines. The names of the disciplines (the Basics of Light Engineering, Photometry, Lighting Installations, Lighting Devices, etc.), as well as brief content of these disciplines, were clearly formalised. These disciplines determined the training of the industry specialists and complied with the speciality.

The education plans of the students of MPEI comprised the specialists and bachelors plans of the 550700 Electronics and Microelectronics programme (the best students graduated from the master's technical and technological programme with this profile too). Both these standards of higher professional education also comprised not only the names of the disciplines, but brief content of the same [3, 4].

Since 2010, the plans have begun to change dramatically. The order of the Ministry of Education and Science [3, 4] does not contain the disciplines and specialities of the 210100 Electronics and Nanoelectronics programme any longer, and contains common and professional competences instead of them, as well as the major professional educational programme (MPEP defined by an institution in accordance with the approximate major educational programme of higher professional education) with standard terms of education and workload in credits (1 credit is equal to 36 academic hours). The area of professional activity of bachelors (masters) is described including "theoretical and experimental research, mathematical and computer modelling, designing, production technology, application and usage of materials, components of electronic instruments, devices, vacuum, plasma, solid-state, microwave, optical, micro and nanoelectronic installations with various functional use"… The types of professional activity were introduced: design activities, production and technological activities, science and research activities, management activities, erection and commissioning activities, service and operational activities.

Since this moment, a graduate should have common and professional competences, and this trend has been increasing although achievement of the required indicators (knowledge, skills, hereinafter referred to as the indicators) are defined by MPEP of a specific institution. Since this moment, the competence approach has become governing.

It is expressly noted that higher education institutions should update the major educational programmes every year with consideration of the development of science, engineering, culture, economy, technologies, and social sphere. This Federal State Education Standard (FSES), as well as FSES [5, 6], noted that MPEP should contain disciplines selected by the students with the scope of at least one-third of the variable part. The procedure of formation of student-selected disciplines was set by the academic board of an institution.

The list of minimal inventory required for the implementation of, for instance, a Bachelor's programme was also defined and included measurement, diagnostic, technological facilities, equipment, and installations, as well as computers united in local networks with the Internet access provided with the licensed software packages for solving tasks in the field of electronics and nanoelectronics.

The Masters' laboratory courses should be equipped with a sufficient number of experimental sets for performing laboratory works by all students of the relevant profile. The number of students using one experimental set simultaneously should not exceed two.

Naturally, based on this FSES, the institutions should get the money required for purchase of such inventory, at least theoretically, so these clauses were just removed from the subsequent versions. Only broad terms were left: "the organisation shall possess educational inventory (premises and equipment) on the right of ownership or on another legal basis." [1, 2]

The 2012 May Orders of the President of Russia kicked off formation of the state policy for the development of the National System of Qualifications and formed the basis of the system of ***professional standards*** as an alternative for the existing system of documents regulating the labour market. On December 9, 2013, the President of Russia V. Putin noted: "The professional standards should become a real reference point for the educational system, a mandatory one – I want to underline it – in the course of development of educational programmes of our universities, lyceums, and colleges." The President of Russia ordered the Government of Russia to take the provisions of professional standards in the course of formalisation of FSES of higher education, after which the process of FSES updating based on the professional standards was organised.

The structure of FSES3++ [1, 2] is significantly different from the previous FSES3+ [5, 6], the FSES itself has a framework nature with an enhancement of the status of approximate major educational programmes (AMEP). The goal of the application of FSES of higher education and AMEP is the unification of the educational area and achievement of the contemporary level of training.

The major MPEP of higher education is still developed and approved by an educational institution (NRU MPEI in our case) based on the requirements of FSES of higher education and with consideration of AMEP. AMEP is a set of educational and methodological documents developed with the consideration of the requirements of the regional labour market, the requirements of federal executive authorities and industry requirements regulating the goals, the expected results, the content, forms, conditions and technologies of educational process organisation, evaluation of the graduate training quality.

The evaluation of the graduate training quality is conducted based on achievement in training the **competences**: universal common competences of FSES and professional competences based on professional standards (UC, CC, and PC respectively). In case of non-availability of professional standards, PCs are formalised on the basis of the requirements analysis to professional activity imposed by the labour market as well as generalisation of domestic and foreign experience, international standards with consideration of industry development trends. The set of competences should provide a graduate's readiness to act in the selected area of professional activity and limited sphere of professional activity.

In the course of MPEP development, it is necessary to take opinions of the parties (employers, enrolees, students, lecturers) interested in education on the basis of this MPEP into account, to define the areas of professional activity of graduates, to select the types of professional activity objectives, and to define the list of major objects (or knowledge areas).

Therefore, the main attention should be paid to cooperation between the institutions (NRU MPEI in our case) and employer.

Despite the fact that the students were trained in the Electronics and Nanoelectronics speciality in the Light Engineering department of MPEI, the high qualification specialists, i.e. Candidates and Doctors, defended and keep defending their theses in the State Commission for Academic Degrees and Titles speciality 05.09.07 Light Engineering [7] contained in the group of specialities 05.09.00 Electric Engineering.

In 2017, the Light & Engineering / Svetotekhnika Journal organised a discussion regarding the description of the speciality and the following generalisation was formulated: "Light Engineering is an area of science and engineering developing the methods of generation, spatial redistribution of optical radiation as well as its transformation into other types of energy and application for various purposes," which significantly broadened the previous variant ("The science speciality uniting theoretical and experimental studies for modernisation of existing and development of brand new sources of artificial light and irradiation"). Within the scope of the speciality, the methods of design of light (illuminating) devices, lighting installations, and photometric monitoring systems are developed, the processes in the volumes of discharge and incandescence light sources, elements of light sources, materials, and light source operation mode control systems are studied. The studies are made for the purpose of development of high-efficient, environment-friendly light sources providing the required aesthetic perception of object, comfort, significant reduction of power consumption, economical efficiency of operation.

Based on the comparison of these formulations, it is already seen that it is proposed to broaden the research areas and, therefore, the specialist training areas.

Due to non-availability of the regulated disciplines in FSES of higher education, the educational institutions, NRU MPEI in this case, have a number of questions again: is light engineering closer to the Electric Engineering or Electronics and Nanoelectronics speciality from employers' point of view? Which competencies (knowledge, skills) do graduates lack?

Naturally, each institution has its permanent employers but it should be clearly understood that technical education is impossible without financial and informational support: both technical equipment of educational and science laboratories with contemporary instruments and clear formulations related to required skills of graduates are required.

Recently, the Ministry of Labour and Social Protection has introduced the professional standards: for specialists in light design and design of innovative lighting installations and for specialists in the development of LED-based lighting devices. However, the professional activity of, for example, the former professional standard is very broad: it includes manufacturing of electric lamps and lighting equipment, development of architectural concepts and development of projects relating not only to electric engineering and electronic equipment but also to mining engineering, chemical technology, visual design, etc.!

In our opinion, it is simply impossible to train a specialist with such a broad area of activities neither in 4 nor in 6 years. The more so because the generalised labour functions listed in this professional standard are much narrower and closer to conventional training of specialists.

The graduate bachelors should design lighting objects and lighting installations and the graduate masters should create lighting objects and installations concepts.

Naturally, the marketing issues should be addressed too.

A light solution designer shall perform the duties that are incompatible with each other at first sight: to be an engineer and an artist at the same time, to develop both the lighting concept and the power supply scheme, to select equipment and to supervise correctness of its installation. However, the lighting engineering department has a large experience in such education. As early as in 1995, professor A.B. Matveev and associate professor V.I. Petrov established a unique speciality Lighting Architecture, Styling, and Advertising. It was established thanks to large experience and talent of Alexander B Matveev who, at the same time with the education in MPEI, graduated from the Moscow Art Theatre School and was not only a Doctor of Technical Sciences but also a good artist as well as a designer of more than 25 performance of the Soviet Army Theatre and many performances of other theatres. As a result, the founders of the speciality and their followers have been successfully training young people in technical skills and elements of artistic perception within the scope of the Bachelor's programme and selected Master's programme disciplines of our university as well as in the postgraduate course Lighting Equipment and Design for more than 20 years.

During the 2018/2019 academic year, the Light Engineering department, as well as the whole faculty, has been keeping preparing new education plans compliant with the FSES3++. The applicable bachelors training education plan adopted in 2016 contained the following common disciplines: Nanoelectronics, Circuit Engineering, Basics of the Electronic Component Base, Materials of Electronic Engineering, Theoretical Basics of Light Engineering, Vacuum and Plasma Electronics, Quantum and Optical Electronics and Solid-State Electronics. We think that the mentioned common disciplines should be kept and that employers and the light engineering community may provide us with significant assistance. We are waiting for proposals with the sections of working programmes or specific themes required by contemporary specialists especially for ones working in the areas mentioned in this article.

The future disciplines of the new bachelors training education plan are being actively discussed by the lecturers of the department, but we think that the light engineering disciplines will include the conventional ones such as Basics of Light Engineering, Computer Graphics, Lighting Devices, Lighting Installations, Introduction to Light Design, Sources of Optical Radiation, Control Gears, and the new ones, e.g. Designing and Manufacturing Technology of LED-based Lighting Devices, Lighting Control Systems, and Light-Emitting Diodes.

The discussion of the disciplines of the new bachelors training education plan has just begun and the Light Engineering department of NRU MPEI is open for suggestions. We would also like to note that the existing plan already comprises the lighting design disciplines such as Technologies of Lighting Design, Computer Graphics in Light Engineering, Lighting Equipment and Design, Modelling and Evaluation of Light and Colour Environment, Daylighting and Artificial Lighting; as well as the areas based on the LED light sources and lighting devices based on them, e.g. Technologies of Development of Light Sources and Control Gears, Equipment and Methods of Lighting, Design of Optical Systems of Light Devices.

Editorial note

We offer all concerned persons to express their suggestions regarding modernisation of the educational system in our journal, to take a direct part in the enhancement of inventory of the Lighting Engineering department for the purpose of quality increase of both graduate trainings and advanced courses for employees of different organisations.

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Light & Engineering
Vol. 27, No. 5, pp. 122–126, 2019
https://doi.org/10.33383/2018-056

NEW REQUIREMENTS TO ENERGY EFFICIENCY AND LABELLING OF LIGHTING PRODUCTS IN THE RUSSIAN FEDERATION

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ABSTRACT

The article describes the main provisions of the Government Decrees of the Russian Federation No. 450 dated on April 15, 2017 and No. 1356 dated on November 2017 regarding lighting products. The necessity to introduce the Technical Regulation of the EEU on energy efficiency requirements to power-consuming products in the territory of the EEU is considered in the article. It is shown that introduction of new requirements to energy efficiency and operational characteristics of general use lamps and luminaires, as well as informing consumers on the energy efficiency of the products, are aimed at lowering of power consumption for lighting and negative environmental impact.

Keywords: energy efficiency, power-consuming products, general use lamps, luminaires, energy labelling, energy efficiency classes, operational characteristics, standards, directives and regulations of the European Union

1. INTRODUCTION

In line with world trends in the area of energy efficiency and increasing of energy efficiency of products, clause 1 of article 10 of the Federal Law [1] provides mandatory availability of information regarding energy efficiency class of products manufactured in Russia and imported to Russia for turnover in the territory of Russia, in technical documentation attached to such products and in its labelling; clause 6 of article 48 of the Law provides mandatory setting of requirements to lighting devices and electric lamps used in AC circuits for lighting. According to the said article of the Law, the Government of the Russian Federation introduces statutory acts on energy efficiency and increasing of energy efficiency of energy-efficient products, including lighting products, aiming at the reduction of power consumption for lighting and lowering of negative environmental impact.

The Decree of the Government of the Russian Federation (hereinafter referred to as the Decree) [2] specifies the types of products (with consideration of their characteristics), including household electric lamps, and approves the list of determination principles (rules) of energy efficiency class of the products by manufacturers and importers. The values of energy efficiency indicators specified in the Decree [2] used for determination of the energy efficiency class of power-consuming products, in particular, household electric lamps, were harmonised with the standards of setting of energy efficiency class of relevant products applicable in European countries.

The Decree [3] approved the requirements to lighting devices and electric lamps containing minimally acceptable values of luminous efficacy (energy efficiency) of electric lamps and luminaires for general lighting.

2. LIGHTING PRODUCTS ENERGY EFFICIENCY REGULATING: INNOVATIONS IN RUSSIAN PRACTICE

The Decree [2] applies the following designations of the energy efficiency classes: *A*, *B*, *C*, *D*, *E*, *F*, *G*. As it is known, the classes *A* and *G* should be used for designation of the products categorised as one category with consideration of their characteristics with the highest and the least energy efficiency respectively.

As soon as the products with maximum energy efficiency significantly exceeding that specified for class *A* were introduced in the market, the Decree [2] was amended for setting of additional classes of energy efficiency: first *A*+, then *A*++ for designation of the products with the highest energy efficiency (in ascending order: *A*+, *A*++). The EU Member States also used similar classes of energy efficiency of products characterising their energy efficiency during operation [4]. For instance, for the purpose of labelling energy efficiency of high-output electric lamps and luminaires meeting the highest requirements of the market in terms of energy indicators, the EU introduced the Regulation [5] setting another two classes of energy efficiency: *A*+ and *A*++.

Over the recent years, as a result of the global technological progress, new efficient technologies which sufficiently outperform the conventional ones in terms of economic efficiency, environmental safety, and qualitative parameters have appeared and reached technological maturity. The products with the highest level of energy efficiency significantly outperforming the levels set for classes *A*+ and *A*++ have appeared in the global market, due to which it has become necessary to specify the class of energy efficiency of such products.

For the purpose of society informing system modernisation on the quality and energy efficiency of power-consuming products, including electric lamps, and acceleration of market transition to energy-efficient technologies, the Decree [6] entered into force since January 1, 2018, in accordance with which, the amendments to the Decree [2] were made.

The Decree [6] specifies the energy efficiency classes *A*+, *A*++, *A*+++ for labelling of power-consuming products with the highest energy efficiency (in ascending order: *A*+, *A*++, *A*+++), i.e. it has become possible to apply an additional energy efficiency class *A*+++.

Another important modification introduced in the Decree [2] by the Decree [6] is an extension of the list of products for which the requirement on availability of energy efficiency class information in the attached technical documentation and in labels of such products applies. The Decree [2] specified the mandatory designation of the energy efficiency class only for household electric lamps, including incandescent lamps with a power of up to 100 W and low-pressure fluorescent lamps. The Decree [6] specifies this mandatory requirement for all types of general use electric lamps, i.e., apart from the household lamps, now this group of light sources includes also the lamps for professional lighting, e.g. for the lighting of offices, public buildings and structures, production facilities, etc.

For fulfilment of the requirements of the Decree [6], it is necessary to formalise the Russian statutory documents regulating uniform regulations and rules concerning the list of indicators related to the energy efficiency of general use electric lamps, which contain the methods of determination of electric lamps efficiency classes and requirements to energy efficiency labels.

For measurement of lighting products indicators, including those related to energy efficiency, the measurement methods according to GOST [7, 8] may be used.

GOSTs related to labelling and information about the power consumption of household electric lamps were developed [9, 10]. However, these standards require actualisation, since new improved lighting technologies have appeared recently and methods of evaluation of their energy efficiency are not reflected in these standards.

Another document regulating labelling and information about power consumption of products, including household lamps, applicable in the Russian Federation is the Order of the Ministry of Industry and Trade of Russia [11], which specifies the rules of determination of energy efficiency class of a product and other information of its energy efficiency by the manufacturers and importers. The rules of determination of the household lamps energy efficiency class set out by this Order are similar to evaluation methods specified in GOST [9], harmonised with the Directive [12] (in relation to energy labelling of household lamps), which was cancelled and replaced by the Directive [13] (on specification of information on power and other resources consumption by power-consuming products in the labelling and standard product information) which, in its turn, was cancelled since August 1, 2017.

It should be expressly noted that the EU conducts constant work related to the development of new directives and regulations on energy efficiency and energy labelling of power-consuming products including lighting products.

In the Member States of the Eurasian Economic Union (EEU), mandatory uniform technical regulations apply to power-consuming products including lighting products. There are two technical regulations for low-voltage equipment and technical means which include lighting products applicable in the territory of the EEU: [14] harmonised with the Directive [15] (on approximation of low voltage equipment legislation of Member States[1]) and [16] harmonised with Directive [17] (on approximation of electromagnetic compatibility legislation of Member States[2]). Moreover, since March 1, 2018, the technical regulation of the EEU [18] harmonised with the Directive [19] is applicable in the EEU; it limits the content of hazardous substances in products, namely the six hazardous substances: lead, mercury, cadmium, hexavalent chromium, polybrominated biphenyls and polybrominated biphenyl ethers.

Compliance with the requirements of technical regulations is provided by the voluntary application of international standards or national standards provided the former have not been developed yet. It is useful to highlight in this regard that the energy efficiency of power-consuming products technical regulation of the EEU (TR EEU) developed with consideration of the latest directives and regulations of the EU has not been approved yet and is being discussed in the international level [20].

One of the Member States of the EEU, the Republic of Belarus, has made a decision on the strengthening of requirements to the energy efficiency of power-consuming products and has introduced the requirement on mandatory confirmation of the energy efficiency parameters compliance since July 1, 2018, which will be applicable until TR EEU comes into effect. This requirement applies to both lighting products manufactured in Belarus and the products imported to this country, namely the household undirected light distribution lamps, fluorescent lamps without built-in ballast, and high-intensity discharge lamps. For implementation of the evaluation procedure, the following standards were adopted in Belarus: the standard [21]; the standard [22], which states that it complies with the Delegated Regulation [23] supplementing the Directive [13] in relation to energy labelling of electric lamps and luminaires, and the standard [24], which states that it takes the requirements of the Regulation [25] into account. As it was noted above, the basic Directive [13] was cancelled in the EU, and the new Regulation [26] of energy labelling of power-consuming products was adopted in the EU since August 1, 2017.

In order to set uniform energy efficiency requirements to lighting products in the EEU Member States and for compliance with the requirements of the Decree [6] in the course of energy efficiency evaluation, it appears to be necessary to introduce TR EEU. Alongside with entering TR EEU into force, the problem of necessity to develop international standards constituting a base of evidence of compliance with the requirements of TR EEU regarding setting of uniform requirements and rules regarding the list of energy efficiency parameters of electric lamps, methods of electric lamps energy efficiency class determination and energy efficiency labelling requirements.

Apart from the Decree [6], in order to reduce costs of lighting and lower negative environmental impact, the Decree [27], in which the requirements to lighting installations and electric lamps used in AC circuits were revised, has entered into force since July 1, 2017. Introduction of this decree is related to the fact that the applicable minimal energy efficiency requirements to lighting installations and electric lamps set out by the Decree [3] do not comply with the current level of development of lighting technologies, therefore, with the Decree [27] entering into force, the Decree [3] was annulled. The Decree [27] introduces new requirements to energy efficiency and operational characteristics of general use lamps and luminaires used in AC circuits for lighting, which will be implemented during two phases: the first phase is from July 1, 2018 to December 31, 2019, the second phase is since January 1, 2020. During phases 1 and 2, the lamps and luminaires should comply with the set requirements to energy efficiency and operational characteristics. During phase 2, the level of real-power losses in ballasts of luminaires for public and production premises with fluorescent or induction lamps should not exceed 8 %.

Given that the Decree [27] was published on the website of the Government of the Russian Federa-

[1] Since 20.04.2016, the Directive [15] was replaced by the newly adopted Directive 2014/35/EU

[2] Since 20.04.2016, the Directive [17] was replaced by the newly adopted Directive 2014/30/EU

tion on November 15, 2017, the manufacturers of lighting equipment have sufficient time (until July 1, 2018) to conduct analytical comparison of the actual values of luminous efficacy (energy efficiency) of their products reached in the course of manufacturing and standardised by the statutory technical documentation with the minimum values of luminous efficacy (energy efficiency) regulated by the Decree. Based on the results of the conducted comparison, the companies should take a set of measures to introduce relevant modifications to the statutory and technical documentation in case the indicators reached during manufacturing are not lower than the ones standardised by the Decree or to make a decision on enhancement of the products to reach compliance of the parameters with the requirements of the Decree with subsequent revision of the statutory and technical documentation. The similar work should be conducted for meeting the requirements of this Decree by operational characteristics of general use lamps and luminaires.

3. CONCLUSION

The requirements set out in the Decrees [6, 27] will: significantly reduce power consumption of the lighting devices; assist in increase of quality of artificial lighting; accelerate market penetration of energy-efficient and high-quality products; assist in establishment of the system of social informing on the quality and energy efficiency of power-consuming products including lighting products; assist in performance of informational and advertising events explaining economical benefits of application of energy-efficient products; establish real barriers on the way of non-energy-efficient and non-qualitative products to the market and provide compliance of the Russian products with the energy efficiency and labelling requirements of the European market which is required for promotion of Russian lighting products to the international market.

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Light & Engineering
Vol. 27, No. 5, pp. 127–133, 2019 *https://doi.org/10.33383/2019-064*

OPTIMISATION OF ILLUMINANCE OF MUNICIPAL FACILITIES AND PROTECTION OF RETAIL POWER CONSUMERS: INTERDEPENDENCE OF PROCESSES

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ABSTRACT

The article characterises the main directions of optimisation of electric power market legal regulation including such its specific segment as illumination of cities within the context of determination of resources for increase of electric energy quality, its saving and protection of consumers (subscribers). Interdependence of the processes of enforcement of the rights and legal interests of electric energy consumers and one of the most energy demanding factors, lighting of municipal facilities, was discovered. It was found that guarantees for electric energy consumers specified by art. 38 of the Federal Law “On Electric Energy” (prohibition of consumption limitations including the so called rolling blackouts, etc.) are detailed by subordinate legislation some items of which require clarification of legal categories of relations between the terms “wholesale” and “retail” market of electric power.

The opinions of the Supreme Court announced in 2019, which provide higher level of legal protection of consumers as the weakest party of legal relations in the examined market, were subject to scientific analysis; it is justified that, in view of the requirements of art. 126 of the Constitution of Russia, they shall become a target for elimination of numerous contradictions in court practice regarding this matter.

Specific propositions on amendments (modification) of some federal laws and acts of the Government of the Russian Federation are specified.

Keywords: electric power, illuminance, light emitting diode (LED), illumination, market, consumer, law, court, legal opinion, service, agreement, quality, methodology, capacity, mode, consumption, modification, unification, explanations, accessibility, municipal formation, process, property, street illumination

1. INTRODUCTION

Based on the results of sociological and other studies conducted by the scientists of Economical Activity Legal Regulation Department (DPRED) of the Financial University under the Government of the Russian Federation in respect of the process of legal regulation of activity, status of and relations between participants of the electric power market, its incompleteness may be acknowledged. Moreover, its implementation (the specific orders were given to the Parliament and the Government of the Russian Federation) is contingent upon a number of negative factors related to particular reduction (instability) of consumption in the electric energy market and growth of electric power costs; for example, the problems related to attempts to obligate natural persons (consumers of retail energy market services) to pay for illumination of facilities which are not the common property of an apartment complex are not taken into account completely, there are numerous claims of subscribers (consumers) regarding the quality of the provided services including the level of illuminance of municipal formations (according to the International Energy Agency, 19 % of all energy consumed in the world is spent for illumination) [1].

The practical aspect of the problem is rather obvious since Russia is the world's third largest producer of electric power significant part of which is spent for illumination of streets and other municipal facilities [2]. Against the backdrop of new geopolitical matters providing growth of expenditures for defence of the country and, hence, increase of social and economical problems, it is necessary to search for new legal instruments providing increase of the share of the electric energy market in the Russian GDP and, on the other hand, to analyse any factors having energy saving potential including for street illumination. As a result, social preferences shall be achieved by retail consumers, for example, those related to reduction of electric energy tariffs. However, unfortunately, contrary processes requiring scientific analysis exist too.

In this context, the relation between theoretical and applied aspects shall be provided by, for instance, not only by elimination of terminological ambiguity ("electric power market", "electric energy market", "resource supply") and appearance of new study categories (electric capacity market providing propositions on introduction of modifications in art. 539 of the Civil Code of the Russian Federation), etc. In terms of research, the most interesting aspect is the method of increase of not only quantity but also quality of electric power in the relevant market (the Federal Law "On Electric Energy" uses the terms "wholesale" and "retail" energy markets) for benefit of the least protected party of the studied social relations, the consumer of electric energy.

The authors of the article presume that the modifications in local governance legislation related to erosion of local significance matters of street illumination provision obligation shall be analysed critically (hereinafter we will provide arguments for this opinion).

Together with implementation of applied propositions (some of them are rather obvious: for example, in the Moscow Gostiny Dvor, with the very high level of illuminance, no louvers which may be shut during night time for significant energy saving are used [2]), a higher level of energy saving in street illumination shall be provided.

2. ANALYTICAL REVIEW (FORMULATION OF THE PROBLEMS OF THE RESEARCH)

The basis of the study comprises contemporary scientific works which propose to increase efficiency of legal regulation of the electric energy market as a whole and, in particular, quality of supplied electric energy and degree of protection of retail electric energy market consumers on the basis of: improvement of competition [3], enhancement of procedures (in particular, conducting of tenders including the so called electronic tenders for construction and repair works) of maintenance of street illumination objects [4], improvement of legal statutes related to protection of rights of subscribers from improper fulfilment of obligations on supply of electric energy [5], setting of particular preferences for small and medium business entities, manufacturers of agricultural products [6], etc.

Special attention was paid to works of the practising experts: judges specialising in reviewing of cases to protect of consumers' rights in the analysed market [7, 8].

Studying of civilised aspects of regulation of the energy services market required reference to monographic studies of supply of resources in the Russian housing and utilities sphere [9], civil regulation of energy exchange [10], including those based on studying of corresponding foreign experience [11].

Websites of energy organisations and other Internet resources were used. For instance, the expert and analytical report of the experts of ENERGYNET NTI workgroup characterises low efficiency of electric power sector as "a major challenge for Russia" "intensification" of which is caused by the fact that contemporary consumers become more demanding for accessibility, reliability and quality of electric energy [12].

In the study, emphasis was laid on the Internet resources which, in particular, review specific opportunity for reduction of energy consumers' expenditures (e.g. economical feasibility of replacement of obsolete lighting sources with state-of-the-art high luminance LED lamps [13].

Online questionnaire of stakeholders and experts regarding the studies matters was conducted; more than 60 enterprises participating in the energy market took part in it. The results of the questionnaire allowed to draw the following conclusions: 22 % of experts presume that the problems of electric energy quality (EEQ) may be solved by means of statutory and legal methods, whereas 33 % of them set their hopes on the so called "technological" combined approach; almost a half of the experts (44 %) point at deficiency of statutory and legal motivation for solving of EEQ. Different categories of the electric energy market consumers are interested in research and solving of EEQ problems to different extents. Rejections to take part in the study are often based on low significance of the problem. It is especially common for electric power generators. For example, the Counsel of Energy Producers flatly refused to provide experts and to take part in expert and project events (it is declared that "members of the Counsel of Energy Producers hold about 70 % of the installed capacity of the United Energy System of Russia"). Necessity of research is often thrown doubt upon by representatives of network companies. Consumers of electric energy are a more interested group, and this matter is studied in this article in detail.

There is similar data of the online questionnaire in respect of irrational lighting of objects which are the most frequently used by natural persons consuming electric energy (for instance, in **corridors and halls**, lighting is turned on in absence of people for 80 % of time) [2].

Some of the most popular websites of the largest companies which are de facto monopolists in work with retail market consumers (for example, the website of the United Energy Company (UNECO): uneco.ru/peredacha-elektricheskoy-energii/uchet-elektricheskoy-energii) were not only studied by the authors of the article but also used by one of them for practical purposes: primary connection of a consumer to the electric network, which uncovered a number of complications in practical application.

3. GOALS AND METHODS OF THE STUDY

The following main goals of the study conducted within the scope of this article may be specified.

1. Determination of the ways of optimisation of legal regulation of activity, status and relations of participants of the electric energy market (retail market in the first instance). In this context, rather significant, in the authors' opinion, problems and legal conflicts may be found. For instance, the basic law in respect of regulation of the analysed social relations, the Federal Law № 35-FZ "On Electric Energy" dated on 26.03.2003 (as amended) does not contain the term "electric energy" among the main terms. Consequently, it is necessary to refer to GOST R52002–2003 which contains a more "technocratic" than legal definition for formulation of the term "electric energy" since it is this product that consumers get.

But the nature of this research task is wide and may be detailed in respect of formulation of theoretical conclusions and practical proposals for increase of the level of legal protection of the largest group of the subjects in the analysed legal relationship: the consumers of electric energy.

The guarantees for electric energy consumers are specified by art. 38 of the Law on Electric Energy (it is prohibited to limit the mode of consumption if there is no indebtedness, including the so called rolling blackouts) and are detailed by subordinate legislation and mostly by the decrees of the Government (the latter de facto set the only real criterion for legal differentiation between the wholesale and retail electric energy markets although is obvious that it requires substantiation (the indicators within the range between 670kW and 759kW are set).

2. Research of the practice of application of the above mentioned and other statutory legal acts in the course of which the initial sense and purpose of the adopted act may be significantly strained; the authors of the article are particularly concerned about the situations when it leads to derogation of rights and legal interests of a subject in respect of which special additional legal protection guarantees are set (e.g. in the consumers' rights protection legislation). Due to the said factor, the reasons for setting of such research goal require additional arguments.

For instance, studying of the court practice allows us to make a conclusion that many of court opinions related to the studied problems are controversial. First we will note those ones in respect of which the opinions of the Supreme Court of Russia were also formulated in 2019, which allows to hope for appearing of a steady direction of court law enforcement (the controversial opinions will be partially characterised further).

The opinions providing a higher level of legal protection of a consumer as the weakest party of legal relationship in the studied market were formulated not so long ago. The judgement № 305-ES18–26293 dated on 23.05.2019 regarding the case

№ A40–200484/2017 contains an opinion according to which, if a subscriber claims that an energy supply company has not sealed a metering device, it is this company that has to prove the contrary. The argument, that a subscriber discovered lack of seals has to address a network or energy supply company, is vicious.

The largest number of disputes and controversial judicial acts were caused by the situation related to the question of whether a consumer is entitled to appeal against a notification on limitation of energy consumption mode. One can only express hope that the opinion expressed in the Judgement № 306-ES18–20653 dated on 15.04.2019 regarding the case № A57–25248/2017, according to which a consumer is entitled to appeal against a notification on limitation of the energy consumption mode and the courts have to check whether such notification is sent reasonably assessing the causes of indebtedness will become an orientation point for all courts.

A similar conclusion may be made in respect of a judicial act № 309-ES18–24456 dated on 23.05.2019 regarding the case № A60–64563/2017: The Supreme Court explained which moment the period of uncounted electric energy consumption shall be counted from if the period between the date of the last scheduled checking of a metering device and the date of discovering of such consumption exceeds a year. It is necessary to take the date when the last scheduled checking before the moment of discovering of the uncounted consumption should have been conducted into consideration.

But there are much more controversial court opinions; there is such situation in relation to the question which legal regulations are applicable to electric power transfer (transport) agreements. Some courts proceed on the basis that legal relationship relating to transfer of electric energy by a network company are regulated by regulations on provision of services for a fee. For instance, the act of the supreme judicial authority № 305-ES18–8863 dated on 27.09. 2018 regarding the case № A40–49067/2017, states that "…Legal relationship for electric energy transfer is mediated by a public service provision agreement…"

According to the second opinion, the legal relationship for transfer of electric energy by a network company is regulated by statutes on provision of services for fee (chapter 39 of the Civil Code of the Russian Federation) with consideration of provisions on power supply agreements (§ 6 of art. 30 of the Civil Code of the Russian Federation). For example, the Ruling of the Court of Arbitration of the Central District № F10–1051/2018 dated on 11.04.2018 with regard to the case № A36–9002/2015 states: "…the courts of arbitration correctly characterised the relations established by the parties as the legal relations arisen from the service provision agreement regulated by chapter 39 of the Civil Code of the Russian Federation…"

Elimination of the mentioned and other controversies is an essential element of improvement of legal regulation of the electric energy market and protection of the rights of consumers (subscribers).

3). The third research goal is obviously linked with the above mentioned ones but is distinctive due to its higher significance for consumers of electric energy. It is related to improvement of the system of monitoring and control of quality of electric energy, adaptation of all-new equipment (sensors, analysers, etc.) which shall comply with specific functional requirements (accuracy of readings) and cost criteria (affordability for consumers). The technical solutions, which provide adaptation of network smart control facilities and which, in our opinion, have a simple nature for consumers not requiring complex mathematical calculations, are promising.

This goal provide determination of interdependence between the processes of protection of electric energy consumers (subscribers) and one of the most energy-demanding processes of illumination of municipal formations. We will further address the specific theoretical and applied aspects of this problem.

A set of scientific knowledge methods was used as the methodological framework of the study. However, the authors of the article consider it necessary to draw attention to the fact that with respect to the studied problem application of mathematical methods is not a goal in itself or a fashionable necessity of a symbiosis of legal and technical studies but is a real necessity caused by the content of corresponding statutory legal acts. For example, let us address the decree of the Government "On Provision of Utility Services to Owners and Users of Premises in Apartment Blocks and Residential Buildings" according to which the amount of payment for electric energy for general house needs is determined using the following formula:

$$P_i^{odn} = V_i^{odn} \times T^{kr},$$

where V_i^{odn} is the amount of electric energy supplied for general house needs during the reporting period for specific premises; T^{kr} is the electric power rate set in accordance with the legislation of a constituent entity of the Russian Federation. But the method of calculation in respect of a consumer becomes even more complicated.

We presume that the nature of this method is rather complex, especially when it is used by consumers of electric energy. For example, different practical approaches to the question whether expiration of the calibration period of a metering device leads to uncounted consumption of electric energy or not are also caused by this circumstance.

There is a section for individual consumers on the UNECO website (uneco.ru/peredacha-elektricheskoy-energii/uchet-elektricheskoy-energii) which contains methodology of calculation of the offered mode of consumption; unfortunately, a consumer is not able to puzzle out this methodology, to select the required mode and, accordingly, the cost of services without assistance of a specialist, which one of the authors of the article ascertained.

The similar conclusions may be made in respect of particular sections of the UNECO website (for example: Requirements to Places of Installation of Metering Devices, Requirements to Devices Metrological Characteristics) etc.

As for the question of interdependence between the processes of protection of consumers (subscribers) of electric energy and one of the most energy-demanding processes of illumination of municipal formation, in our opinion, previously the nature of legal regulation of the latter concept had been rather clear and non-controversial.

For instance, in the Law № 443-FZ dated on 28.12.2013 "On General Principles of Local Governance in the Russian Federation", the provisions directly classifying the obligation of street illumination as a matter of local significance became invalid (clause 21 of article 14 "Arrangement of Street Illumination and Installation of Street Signs and Building Numbers" is not applicable any longer). Nowadays, the said statutory act contains only article 45.1 (introduced by the Federal Law № 463-FZ dated on 29.12.2017) with, in our opinion, a rather vague nature of imposing of the analysed obligation ("The rules of landscaping of the territory of a municipal formation shall be approved by a representative body of a relevant municipal formation. The rules of landscaping of the territory of a municipal formation may regulate the matters: …4) of organisation of illumination of the municipal formation territory including architectural illumination of buildings and structures.").

4. RESULTS OF THE STUDY

For the purpose of optimisation of legal regulation of the electric energy market as a whole and improvement of legal guarantees of protection of a relevant consumer, we consider it is necessary:

– Since the Federal Law № 35-FZ dated on 26.03.2003 "On Electric Energy" does not contain the term "electric energy" among the main terms, it is necessary to supplement art. 3 with the following term: "Electric energy means a technically complex product (an assembly of charged particles carrying an elementary electric charge) supplied to a wholesale consumer or a retail consumer (subscriber) in accordance with art. 539 of the Civil Code of the Russian Federation".

– For the purpose of protection of the rights of consumers from improper fulfilment of obligations related to supplies of electric energy (power), we propose:

1. To supplement clause 1 of article 13 of the Federal Law of November 23, 2009 № 261-FZ "Concerning Energy Saving and Increasing Energy Efficiency and on Amending Certain Legislative Acts of the Russian Federation" with the following text: "requirements to characteristics of metering devices as well as to quality of the used energy resources shall be defined in accordance with the legislation of the Russian Federation";

2. To specify a provision stating that obligation of street illumination is one of the matters of local significance in the Federal Law № 443-FZ dated on 28.12.2013 "On General Principles of Local Governance in the Russian Federation";

3. To introduce modifications and an amendment in section X of the Rules (the Decree of the Government of the Russian Federation № 354 dated on 06.05.2011 (as amended on 13.07.2019) "On Provision of Utility Services to Owners and Users of Premises in Apartment Blocks and Residential Buildings") regarding provision of a utility service with improper quality relating to quality of electric energy;

4. To introduce modifications in departmental statutory legal acts regarding electric energy quality monitoring, in particular, in the Rules of Electric Energy Monitoring [The Rules of Electric Energy Monitoring: approved by the Ministry of Fuel and Energy of the Russian Federation on 19.09.1996 and by the Ministry of Construction of the Russian Federation on 26.09.1996);

5. To introduce the following modifications and amendments in the Main Provisions of Functioning of Retail Electric Energy Markets: to impose obligation of maintenance of an installed and approved for operation monitoring device, its safety and integrity as well as safety and integrity of seals and/or visual control signs, reading and storage of its readings and timely replacement on owners of electric energy monitoring devices;

6. To introduce modifications and amendments in the Order of the Ministry of Industry and Trade of the Russian Federation № 57 dated on January 21, 2011 "On approval of methodology recommendations for technical requirements to water, gas, heat energy and electric energy metering systems and devices" regarding setting of technical requirements to electric energy metering systems and devices related to determination of quality of electric energy.

7. To supplement art. 10 of the Federal Law № 209-FZ dated on 24.07.2007 (as amended on 26.07.2019) "On Development of Small and Medium Business in the Russian Federation" with the following provision:

– "16) In those constituent entities of the Russian Federation where tariffs and reduced social standards of electric energy consumption are not specified, the state authorities of the constituent entities of the Russian Federation have the authority to provide support for individual entrepreneurs and heads of agricultural enterprises registered in these regions carrying out production and/or other economical activities in agriculture in accordance with art. 25 of the Law "On Development of Small and Medium Business in the Russian Federation" and art. 2 of the Law "On Agricultural Enterprises".

With consideration of adoption of a number of above characterised legal opinions of the Supreme Court of Russia in respect of consumers of electric energy services (if a subscriber claims that a power supply company has not sealed a metering device, it is this company that shall prove the contrary (1); a consumer is entitled to appeal against a notification on limitation of energy consumption mode and the courts shall check whether such notification had been sent reasonably assessing the causes of indebtedness (2); if the period between the last scheduled checking of a metering device and the date of discovering of uncounted consumption exceeds one year, It is necessary to take the date when the last scheduled checking before the moment of discovering of the uncounted consumption should have been conducted into consideration (3) and a number of other opinions, it is necessary to adopt a Resolution of the Plenum of the Supreme Court of the Russian Federation "On Practice of Reviewing of Cases with Participation of Electric Energy Consumers by Courts."

Such necessity is also caused by the fact that even opinions of the Supreme Court of the Russian Federation do not become orientation points for provision of uniformity of court practice (we already gave such example: The Ruling of the Chamber for Commercial Disputes of the Supreme Court of Russian Federation № 305-ES18–8863 regarding the case № A40–49067/2017) and, in accordance with art. 126 of the Constitution of Russia ("The Supreme Court of the Russian Federation… provides explanations for matters of court practice"), such task may be completed by the supreme judicial authority by adopting the said judicial act.

Otherwise, unfortunately, the researchers' expectations that, for example, before improvement of the law and establishment of the automatic monitoring system, the judges will have to avoid formalism in resolving specific cases will be just vain wishes. The courts of arbitration shall elaborate new approaches to non-monitored consumption in respect of good faith electric energy consumers not interfering into the metering system when there are no proofs of actual corruption of energy resources consumption volume data given that energy consumption monitoring functions shall be performed by professional energy companies. It is not acceptable to presume a consumer's guilt for uncounted consumption of electric energy without considering actual condition of a metering device and good faith of the latter.

And finally, we would like to express a wish for the administration of the UNECO website regarding simplification of information addressed to citizens; we have a similar opinion regarding complex methods of calculation of consumed electric energy (the Decree of the Government of the Russian Federation № 354 dated on 06.05.2011 (as amended on 13.07.2019) "On Provision of Utility Services to Owners and Users of Premises in Apartment Blocks and Residential Buildings") which are probably acceptable for participants of the analysed wholesale market but not for subscribers.

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VOLUME 27 NUMBER 6 2019

LIGHT & ENGINEERING

(SVETOTEKHNIKA)

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