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Theoretical justification and practical aspects of implementation of Human Centric Lighting Program* in production conditions

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Abstract

The relevance of the introduction of HCL systems in production conditions, in which the dynamics of changes in the characteristics of light flux can be synchronized with the circadian biorhythms of the human body. This is determined by the fact that the unsatisfactory characteristics of industrial lighting increase the risk of injury and occupational morbidity. It is shown that providing only normative quantitative characteristics of illumination is not enough, since its qualitative characteristics – ripple coefficient, spectral composition cause non-visual effect of light. They can affect the psychophysiological state of a person, his\her performance, fatigue by affecting the circadian biorhythms of the body. The comparison of standard values of the level of artificial lighting of jobs in different countries with natural ones. Based on the analysis, recommendations were developed aimed at improving artificial lighting. The analysis of the results of the study of non-visual effect of the pulsation of the light flux on the psychophysiology of a person was carried out. Its main negative consequences are given, the necessary tasks for the implementation of the HCL program in a production environment in this aspect are identified. The results of analysis of studies of the influence of the color temperature of the light flux on the psychophysiological state of a person are also presented. Recommendations on the regulation of this parameter for various types of production activities have been developed.

Keywords: industrial lighting; NIF-effect; occupational injuries.

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Introduction

Human production activity is realized, most commonly, in the conditions of action of a complex of negative factors of the production environment. The result of their action is manifested in the occurrence of occupational injuries and occupational diseases, reduced occupational productivity [1, 2]. According to statistics, this fact leads to the occurrence of annual industrial accidents in the world totaling about 250 million, of which about 220 thousand are fatal. In addition to the social component of this situation, at this time the economic losses from industrial accidents, occupational diseases and occupational diseases are about 4% of world GDP.

Formulation of the problem

According to the International Labor Organization (ILO), working conditions characterized by the increased risk of injury, occupational disease also include those characterized not only by the presence of chemicals, noise, etc. in the work area, but also unsatisfactory characteristics of artificial lighting. In different types of production activities, the number of accidents associated with unsatisfactory lighting is 30...50% of their total number [1, 2].

As practice shows, when designing lighting installations in most cases the main attention is paid to ensuring the quantitative characteristics of the luminous flux, i.e. to ensure the normative illumination of the working area – E_n. At the same time, studies show that the qualitative characteristics of light flux (spectral composition, pulsation coefficient) not only affect the formation of human visual perception, but also Non Image Forming Effect [3, 4]. That is, it is determined that the nerve channels of the human visual analyzer transmit complex information that ensures the implementation of not only visual functions, but also, depending on the qualitative characteristics of light flux, can positively or negatively affect the physical and psychological state of a human. In relation to working conditions, it is the efficiency, the level of fatigue of the employee. It follows from the above that to ensure proper lighting of the workplace only by the level of illumination, i.e. by quantitative characteristics,

* Human Centric Lighting (HCL) is artificial lighting, the characteristics of which are adapted to the human body

is insufficient. Taking into account the quality indicators of artificial lighting is especially important at the present time, when fundamentally new light sources are used in lighting systems – LEDs, the use of which, without proper consideration of their characteristics, can lead not only to the deterioration in the vision of workers, but also to the violation of his/her psychological, physical state of health.

The modern direction of providing effective, safe for humans, artificial lighting, taking into account the features of the human visual analyzer, is the development of lighting systems, the characteristics of which are adapted to the human body (HCL) [5]. The available publications in this area of research are mainly aimed at solving the problem in the system "human – living environment" or do not contain the integrated approach to solving the problem. Therefore, the analysis and systematization of published research results on the influence of both quantitative and qualitative characteristics of the luminous flux on the physical and psychological state of the human in order to implement HCL program in the production environment is relevant.

Analysis of recent research and publications

During the evolution of a human, his/her visual analyzer and organism have adapted to the natural diurnal and seasonal changes of natural light – the level of illumination, spectral composition. As a result, natural changes in natural light during the day formed the system of circadian biorhythms of the human body. In this system, the elements of the retina, which are not involved in the formation of the visual image, transmit light energy to the non-visual parts of the brain, which regulate the neuroendocrine system of the body and determine its circadian biorhythms (Fig. 1) [6]. As a result, this system, responding to the characteristics of the light flux, controls and regulates blood pressure, hormonal secretion – in total about 300 physiological functions of the human body.

Presentation of main material

Influence of quantitative characteristics of light flux on the human in production conditions. According to the regulations in force in Ukraine, EU countries, the level of illumination of the working area when performing, for example, design and construction work, is regulated within $E_n = 300...750$ lux [7, 8]. The levels of natural light, to which the human visual analyzer is adapted, are characterized by the following values: – summer noon (1:00 p.m.) with the clear sky – 100 000 lux; – summer noon (1:00 p.m.) with the darkened sky – 50 000 lux; – autumn-winter period (1:00 p.m.), the sky is covered by clouds – 3000...2000 lux. That is, if illumination $E = 2500$ lux was provided at the workplace, then this would be correct for the human light sensation, which corresponds to the conditions of natural lighting on the cloudy autumn day. Based on this, it follows that the established normative values of the illumination level of the working area are much lower in comparison with the natural conditions of operation of the human visual analyzer.

The results of experiments [9] confirm the need to increase the level of illumination in production conditions. According to publications, increasing the level of illumination to $E_f = 2000$ lux in the metallurgical industry has reduced the level of injuries by 52%. When conducting the similar experiment in the conditions of assembly production, the illumination of the working area was set within $E_f = 1500...2500$ lux. Under such conditions, the percent of defective goods decreased by the average of 25...30% while increasing productivity. So, it is obvious that in addition to reducing the level of industrial injuries, ensuring such quantitative characteristics of the illumination of the working area, taking into account the features of the human visual analyzer,

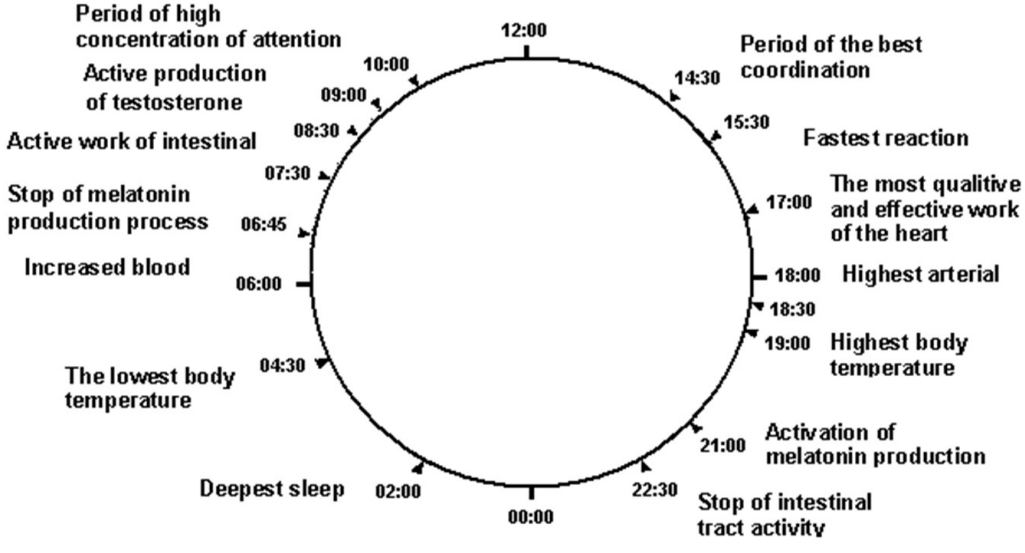

Fig. 1. Circadian biorhythms of the human body*

* For the basis of Fig. 1, the information was used from https://bud-v-forme.ru/news/tsirkadnye-ritmy-tema-udostoennaya-nobelevskoy-premii/

allows not only to increase labor safety, but also to improve the economic performance of production.

Influence of pulsation of the light flux on the human in industrial conditions. The human visual analyzer perceives light pulsations as visual sensations if their frequency does not exceed a few tens of Hertz [10, 11]. That is, if there is the pulsation of the light flux in the visual information perceived by the human visual organs, the frequency of which is lower than the indicated one, then it affects the human retina, then enters the optic tract and is analyzed in the primary visual cortex of the brain. Such information is presented in the form of direct visual sensation of the human. If the pulsation frequency of the light flux is higher, then the visual analyzer of the human as a whole continues to perform the functions of perception of visual images. But, in this case, such information causes the so-called NIF effect, and affects the human nervous system. In this case, the light flux that enters the human eye spreads through non-visual nerve fibers to the circadian system of the hypothalamus, which is the non-visual part of the brain. As a result, its elements are forced to function in the unusual rhythm of nervous activity. Ultimately, this negatively affects the circadian rhythms that are characteristic of the body of each individual (Fig. 1). As a result, the light flux controls the human state at the level of hormonal changes, affects his/her psyche, performance, can lead to "circadian stresses" [10].

The result of the negative non-visual impact of the pulsation of artificial lighting on human health is a feeling of discomfort, premature fatigue, headache, difficulty concentrating on complex work. Moreover, such symptoms occur when performing production tasks in the normative level of illumination (E_n). Experiments have shown that as a result of reducing the pulsation of light flux from 55% to 5...7%, there is an increase in productivity within 30% [2, 11].

Influence of spectral characteristics of light flux on the human in production conditions. It is known that the results of basic research have made it possible to detect a new, fifth photoreceptor in the retina of the human eye – melanopsin. It is significant that melanopsin can significantly affect the level of melatonin in the blood – a hormone of fatigue or sleep, which depends on the spectral components (color temperature of radiation) of the active light flux [3, 5]. Functionally, melanopsin cells are able to generate such nerve impulses, acting on those parts of the cerebral cortex, which represent the main center of regulation of the human autonomic nervous system. That is, melanopsin cells perceive the time of day (day or night) entering the organ of vision along with light, transmit it through non-visual neural channels to the hypotolamus, which directs biological and mental processes in the human body, including regulating hormonal balance (levels of melatonin, cortisol and serotonin) [3, 5, 12]. *Cortisol* is a hormone, the amount of which depends on the level of energy supply of the body. In humans, the highest concentration of cortisol is observed in the morning. With the approach of evening time, the intensity of the production of this hormone gradually decreases. The consequence of this process is a gradual decrease in productivity. *Serotonin* is a hormone that is biologically designed to support, regulate the psycho-emotional balance of the human body. According to research, serotonin deficiency can cause depression in humans.

In the applied aspect, the fact that the greatest sensitivity of melanopsin cells is observed in the blue region of the visible spectrum of radiation (wavelength range $\lambda = 446...477$ nm) is important for solving this problem.

Therefore, based on the above, it follows that a significant number of body functions and its circadian rhythms are related and largely determined by the dynamic changes in the qualitative characteristics of natural light. It is obvious that the parameters of light flux under artificial lighting can also have a significant impact (both positive and negative) on the circadian rhythms of the human body. For example, lighting of the working area during the day (during working hours), in the spectrum of which there will be a high level of the blue component, can lead to a significant underestimation of the level of melatonin production – the so-called fatigue hormone, which increases the likelihood of an accident.

In addition, the so-called "light history" of the human body is of great importance in terms of health, well-being, and level of efficiency. It reflects the range of changes in the level and spectral components of the light flux influencing it during the day [12]. This characteristic actually regulates the amount of hormones produced by melatonin throughout the day. The parameters of this biological cycle depend on the diffe-

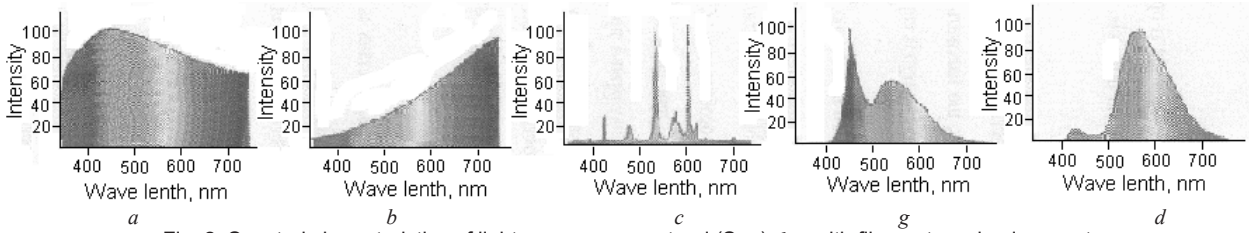

Fig. 2. Spectral characteristics of light sources: *a* – natural (Sun); *b* – with filament; *c* – luminescent; *g* – cold white LED; *d* – warm white LED*

* For the basis of Fig. 2, the information was used from https://elektrik-a.su/osveshhenie/pribory/osveshhenie-dlya-rastenij-svetodiodnoe-285

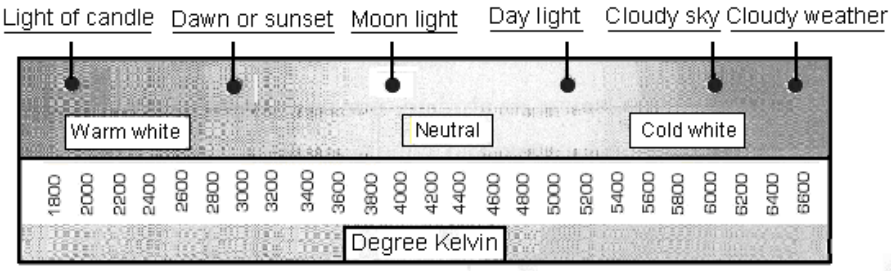

Fig. 3. Color temperature of white LED light sources and healthy human visual perception*

rence between the amplitudes and spectral characteristics of artificial lighting during the day. The results of research show that the human well-being and ability to work depend on the amplitude of the circadian rhythm of melatonin production: human activity increases with increasing amplitude.

The color temperature of the Sun's radiation varies from 2500...3000 K in the morning and in the evening, and up to 5500...6500 K during the day. Comparison of the correspondence of the spectral parameters of artificial light sources with natural ones is presented in Fig. 2.

Applied aspects of HCL program implementation in production conditions. Based on the above theoretical foundations, it follows that the ideology of HCL program is based on the following two main provisions: – the working person must be influenced by the luminous flux of artificial light with the necessary quantitative and qualitative characteristics at the right time; – the level of illumination of the working zone needs to be regulated according to the performed production tasks and mode of work and rest.

Currently, the development of the lighting industry is focused on the use as a main artificial light source – white LEDs, the light flux of which is formed by the spectra of blue (450...460 nm) crystal radiation mixed with green-yellow-red phosphor glow. Moreover, modern technology allows to design LED light sources to obtain any color. According to the characteristics of color temperature, the following classification of white LEDs is used [13].

- WW (Warm White) – warm white color of radiation, the color temperature of the light flux is in the range of 2700...3300 K.
- NW (Neutral White) – neutral white color of radiation with the color temperature range of 3300...5000 K.
- CW (Cool White) – cold white color of light flux, the color temperature of which is above 5000 K.

According to human visual perception, the light flux of the first type of LEDs corresponds approximately to the illuminance created by the sun, which is on the horizon. The light flux of the second type is perceived by the human as sunlight at 12...13 hours in clear weather, and the third – at the beginning of the range approximately corresponds to the light flux of the sun at its zenith, and at 6500...7500 K – natural light during the day and cloudy weather (Fig. 3).

The second important characteristic of the artificial light source is the Color Rendering Index (CRI) or Ra. This indicator shows the degree of adequacy of the reproduction of natural shades of color of the lighting object [14]. Regarding LED light sources, the color rendering index is divided into the following four classes [14]:

Class 1 – the value of Ra (CRI) = 100. This value characterizes the maximum color rendering, that is, such artificial lighting is equivalent to the perception of color when illuminating the object with the natural light source.

Class 2 – the value of Ra (CRI) = 100...90. It is recommended to use light sources with this value of Ra to illuminate places where the most accurate color reproduction is required (art workshops, lighting laboratories, architectural design departments).

Class 3 – the value of Ra (CRI) = 90...80. Light sources with this value of Ra (CRI) are recommended for use in general lighting systems of computer and information centers.

Class 4 – value of Ra (CRI) < 80. Light sources of this class are recommended for illumination of premises with a short stay of human.

Conclusions

The ideology of "Human Centric Lighting" program in production conditions can be implemented by the artificial lighting system with the function of regulating the color temperature of light sources. During the standard production process in working hours, the light sources must provide the color temperature of about 4000 K. In the case of important negotiations, artificial light sources must provide the color temperature within 5000 K. Light sources with the higher color temperature – 8000...11000 K is recommended for use after the field test, as white light with the blue tone may not be acceptable for all workers. In the rooms intended for rest and relaxation it is recommended to provide color temperature of light sources about 3000 K.

* For the basis of Fig. 3, the information was used from http://www.altie.ru/articles/351-tsvetovaya-temperatura-svetodiodnih-lamp-i-svetilnikov.html

Теоретичні й практичні аспекти реалізації програми “Human Centric Lighting” у виробничих умовах

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Анотація

Обґрунтовано актуальність впровадження у виробничих умовах програми реалізації керованих систем штучного освітлення, в яких характеристики світлового потоку можуть динамічно змінюватися відповідно до природних процесів організму людини (програма HCL). Актуальність впровадження визначається тим, що незадовільні характеристики освітлення робочої зони призводять до підвищення ризику одержання травм, професійних захворювань. Визначено, що забезпечення тільки нормативних кількісних характеристик освітленості робочої зони є недостатнім, тому що її якісні характеристики – коефіцієнт пульсації, спектральний склад викликають невізуальну дію світла (NIF). Вони можуть діяти на психофізіологічний стан людини шляхом впливу на циркадні біоритми її організму та впливати на працездатність, рівень стомленості працівника. Це обумовлено тим, що циркадні біоритми організму протягом його еволюції залежать від динаміки зміни комплексу характеристик світлового потоку. На основі порівняння із природним освітленням проаналізовано нормативні значення рівня штучного виробничого освітлення у різних країнах. На основі аналізу розроблено рекомендації, що спрямовані на адаптацію штучного освітлення до організму працюючої людини. Проведено аналіз результатів дослідження невізуального впливу пульсації світлового потоку на психофізіологічний стан людини. Наведено основні негативні наслідки такої дії, визначено необхідні завдання для реалізації програми HCL у виробничих умовах у цьому аспекті. Викладено також результати дослідження впливу колірної температури світлового потоку на психофізіологічний стан людини. Розроблено рекомендації з регулювання цього параметра для різних видів виробничої діяльності.

Дослідження були проведені з урахуванням сучасного напрямку розвитку джерел світла – світлодіодів.

Ключові слова: виробниче освітлення; NIF-ефект; виробничий травматизм.

Теоретические и практические аспекты реализации программы “Human Centric Lighting” в производственных условиях

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Аннотация

Обоснована актуальность реализации программы HCL в производственных условиях. Это вызвано тем, что неудовлетворительные характеристики производственного освещения повышают риск травмирования, профессиональной заболеваемости. Показано, что обеспечение только нормативных количественных характеристик освещенности недостаточно, так как ее качественные характеристики – коэффициент пульсации, спектральный состав вызывают невизуальное действие света. Они могут влиять на психофизиологическое состояние человека, его работоспособность, уровень усталости, воздействуя на циркадные биоритмы организма. Проведено сравнение нормативных значений уровня искусственного освещения рабочих мест с естественным, разработаны рекомендации для его совершенствования. Проведен анализ невизуального действия пульсации светового потока на психофизиологию человека. Определены задачи для реализации программы HCL в производственных условиях в этом аспекте. Изложены результаты исследований влияния цветовой температуры на психофизиологическое состояние человека. Разработаны рекомендации по регулированию этого параметра для различных видов производственной деятельности.

Ключевые слова: производственное освещение; NIF-эффект; производственный травматизм.

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