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METHOD OF ADAPTIVE CONTROL OF EFFECTIVE ENERGY LIGHTING OF GREENHOUSES IN THE VISIBLE OPTICAL RANGE

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Abstract

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Requirements to the set of regulated measurable parameters of microclimate of industrial greenhouses have been imposed. The mathematical model of the process of monitoring artificial illumination of greenhouse crops using the results of measuring effective illumination in the visible optical range, taking into account daily dynamics of natural light, has been further developed. A method and structural algorithmic organization of adaptive monitoring and control of irradiance of greenhouses have been proposed to ensure effective plant photosynthesis.

Key words: illumination; control; spectrum; greenhouse; adjustment
List of abbreviations: AIC – agro-industrial complex, LED – light emitting diode, NI – national instrument, SHEI – state higher education institution

Introduction

Nowadays one of the main indicators of the state development in social and economic sphere is food security level. Achievement of the necessary state, at which the population of the country at every moment of time has physical, social and economic access to a sufficient quantity of quality food meeting their needs and allowing active and healthy lifestyles, is largely determined by the level of development of the national agro-industrial complex (AIC). Taking into account climatic, geographical, structural and sectoral features of agriculture development in individual countries and regions, forms of plant growing under protected cultivation are becoming increasingly popular. The main technical task of such enterprises is year-round (constant) maintenance of optimum climatic conditions for cultivated crops. In this connection, there arises the need to solve a problem of modernizing modern ecosystems with protected soils for crop production on the basis of development and implementation of modern methods and tools for measuring monitoring and controlling processes of photosynthesis of greenhouse flora. The solution of this scientific and technical problem will allow developing a scientific approach to the justification of effective agrotechnical measures to improve production rates and economic capacity of agricultural greenhouses (Tikhomirov et al., 2000; Bakharev et al., 2010). The purpose of the article is development of scientific theoretical and practical studies on increasing productivity of industrial greenhouse complexes on the basis of justification of the method and structural and algorithmic organization of adaptive measuring monitoring and control of effective illumination in the visible optical range, taking into account daily dynamics of natural light.

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Materials and Methods

The topical scientific and applied problem of method substantiation, as well as the mathematical model and the structural and algorithmic organization of the means of adaptive measuring control of effective irradiance of greenhouses made of modern structural materials (cellular and solid polycarbonate) were solved in the article. This method differs from the existing ones due to adapting operating modes of LED light sources for greenhouses (types and number of LEDs involved in the luminaire) based on the results of measuring irradiance in the given spectral range to the types and regimes of growing vegetable crops (cucumbers and tomatoes).

The research methods are based on fundamental principles of the theory of computerized measurement systems, the theory of random processes, the theory of planning a scientific experiment, computer and simulation modelling. Experimental data were obtained in laboratory conditions of the Department of Electronic Engineering of the SHEI 'Donetsk National Technical University' on physical models of computerized information and measuring systems using metrologically certified measuring instruments. Simulation of the developed system was carried out in modern software packages: Mathcad, Microsoft Excel, Proteus, NI LabView.

The results of the research are implemented in the state budget research topics of DonNTU: ‹Efficiency increase of electronic devices and systems›, ‹Development of intelligent measuring modules for electronic systems for monitoring physical media parameters›, ‹Development of methods and tools for efficiency increasing of computerized information and measuring systems of technological processes›. This research was approved at the 21st international exhibition elcomUkraine (April 11-14, 2017, Kyiv, Ukraine) with the assistance of Phoenix Contact (Ukraine).

Results

Having analysed the existing regulatory requirements for the principles of growing greenhouse flora under protected cultivation (Tikhomirov et al., 2000; Departmental rules of the technological engineering NTP 10-95, 1996; Departmental rules of the technological engineering VNTP APK–19–07, 2007; Departmental rules of the technological engineering NTP APK 1.10.09.001-02, 2003; Management of the Greenhouse Environment, 2017), it was established that data on illumination level with allowance for physiologically significant zones are the initial ones for setting corrective effects of controlling technological modes of heating, humidification, ventilation and plant feeding with Carbon dioxide. Based on the analysis of the results of experimental and theoretical studies in the field of light culture of greenhouse plants (Tikhomirov et al., 2000; Bakharev et al., 2010), it was discovered that algorithms for functioning of systems for illumination of greenhouse crops should be adaptive to the types of crops grown and periods of their growth. So, for example, for the cucumber the following ratio of energies over the spectrum is recommended: in the wavelength range from 380 to 490 nm ($\Delta\lambda_{blue}$) – 20%, from 490 to 590 nm ($\Delta\lambda_{green}$) – 40%, from 590 to 700 nm ($\Delta\lambda_{red}$) – 40%; for the tomato: ($\Delta\lambda_{blue}$) – 20%, ($\Delta\lambda_{green}$) – 15%, ($\Delta\lambda_{red}$) – 65%. Level of radiance can vary in the range from 150 to 300 W/m^2 and depends on the periods of flora growing vegetation (Departmental rules of the technological engineering VNTP APK–19–07, 2007; Departmental rules of the technological engineering NTP APK 1.10.09.001-02, 2003). Therefore, in order to implement adjustment of microclimate parameters of greenhouses that affect the yield and productivity indicators, it is necessary to perform measurements of effective radiance in the visible wavelength range in real time operation, and then automatically adjust modes of illumination of greenhouse crops. In the view of the foregoing, the realization of automatic control of technological modes for effective photosynthesis of greenhouse flora is impossible without the development of adaptive methods and means for controlling the effective illumination, taking into account natural and artificial components for the subsequent correction of illumination modes. The relative measurement error of radiance should not exceed ±20%.

Based on the results of previous studies by the authors in (Laktionov et al., 2016; Laktionov et al., 2017), a generalized algorithm for adaptive monitoring and illumination control with a subsequent adjustment of parameters of technological processes in industrial greenhouses, is presented in the form of a block diagram in Figure 1. The number of measurement points, as well as the layout of sensing elements of the monitoring device, are selected on the basis of recommendations given in the document (GOST 24940-96, 1997), proceeding from the features of greenhouse complexes construction. To justify the structural algorithmic organization of the meter being studied, it is necessary to develop a mathematical model for control process of illumination intensity at different sections of wavelengths of visible radiation, which should be correlated with the empirical characteristic of the relative spectral efficiency of photosynthesis (Tikhomirov et al., 2000; Bakharev et al., 2010). The first step in the process of monitoring effective radiance of greenhouses (see Figure 1) is measurement of the integral level of natural illumination. External illumination from a natural light source is described by the normalized spectral characteristic of a standard light source D65 (GOST 7721-89, 1990) (see Figure 2, 1).

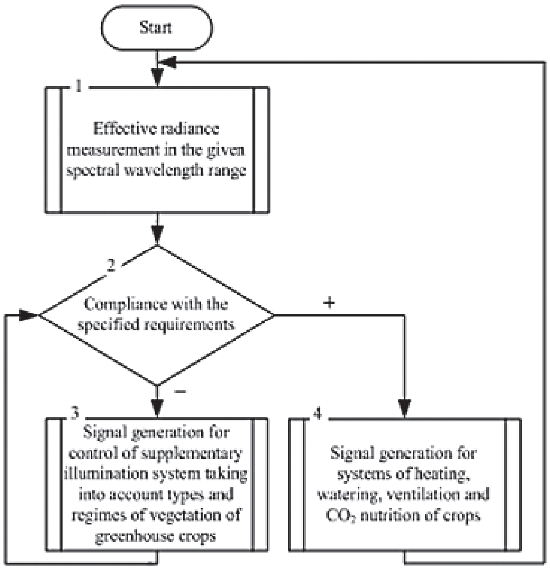

Fig. 1. Generalized algorithm for monitoring and controlling illumination with subsequent adjustment of technological parameters

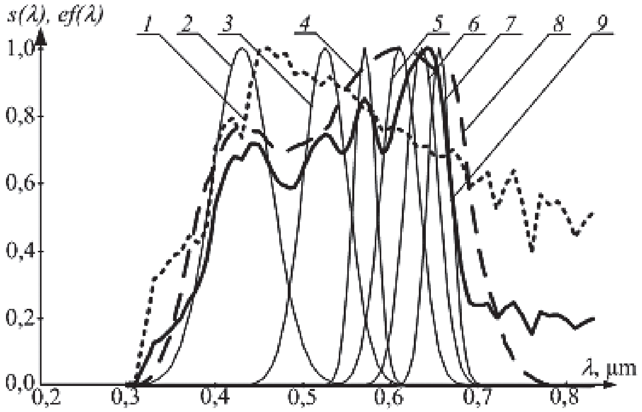

Fig. 2. Spectral distribution of indicators of photosynthesis efficiency of greenhouse flora: 1 – normalized spectral characteristics of external illumination; 2 – 7 – normalized spectral characteristics of LED power: blue (2) with central radiation length λ0 = 0.430 µm; ultra green (3) 0.525 µm; green (4) 0.570 µm; super red (5) 0.610 µm; red (6) 0.635 µm; ultra red (7) 0.655 µm; 8 – necessary relative spectral efficiency of photosynthesis; 9 – relative spectral efficiency of photosynthesis, obtained as a result of the use of LEDs and external illumination

To provide the necessary illumination of greenhouse plants, the authors used light-emitting diodes (LED), which have a number of advantages with respect to other types of artificial light sources (Bakharev et al., 2010). Having analysed characteristics of commercially available LEDs, we proposed to use LED of Bet Lux Electronics BL-L324. LED data have maximum luminous intensity from 1800 to 5000 mcd with a DC current of 30 mA, as well as half the divergence angle a=13º (Bet Lux Electronics. Bullet Type LED lamp, 2017), respectively, the total radiation angle is 26º. The spectral characteristics of the radiation power of LEDs are approximated by a functional dependence, with a relative approximation error not exceeding ±3%:

$$S_{LED}(\lambda) = S_0 s_{LED}(\lambda) = S_0 e^{-r^2(\lambda-\lambda_0)^2},$$

where S_{LED} – spectral power density of radiation; S_0 – spectral power density at wavelength λ_0 – lambda; $s_{LED}(\lambda)$ – normalized spectral power density of LED radiation; r – parameter that determines the half-width of LED emission spectrum; λ – lambda – wavelength of optical radiation; λ_0 – lambda – central wavelength of LED radiation.

Types of commercially available LEDs and their parameters (see Table 1) were selected on the basis of the results of studies carried out by mathematical modelling methods (see Figure 2), taking into account minimum deviation (σ) of the spectral composition of an artificial light source for greenhouses (see Figure 2 – number 9) of the necessary relative spectral efficiency of photosynthesis (see Figure 2 – number 8). The parameters of LED (λ_0 ,Δλ, r), given in Table 1, are obtained by approximating their electro-optic characteristics (Bet Lux Electronics. Bullet Type LED lamp, 2017). Having analysed the simulation results (see Figure 2), we established that the deviation (σ) in the entire wavelength range of visible light does not exceed 9%, which is an order of magnitude lower than existing systems (Bakharev et al., 2010).

Performance comparison of LED parameters (see Table 1) shows that different types of LEDs have a considerable scatter in terms of light intensity. For a proper comparison of this parameter with a range of measurements of radiance stated in regulatory documents (Departmental rules of the technological engineering NTP 10-95, 1996; Departmental rules of the technological engineering VNTP APK–19–07, 2007; Departmental rules of the technological engineering NTP APK 1.10.09.001-02, 2003) we developed a mathematical model of the process of controlling artificial illumination of greenhouse crops by measuring effective illumination in the visible optical range, taking into account daily dynamics of natural light. The model is based on the transformation of optical characteristics of radiation from light (v) into energy (e) system according to the given sequence:

Table 1
LED types and their parameters that provide spectral efficiency of photosynthesis

LED type	Colour of the emitted light	λ_0, μm	Δλ, μm	r, μm^{-1}	I_v, mcd
BL-L324BC	blue	0.430	0.040	20.8	1800
BL-L324PGC	ultra green	0.525	0.030	27.7	5000
BL-L324UGC	green	0.570	0.015	55.5	1800
BL-L324LRC	super red	0.610	0.025	33.3	2000
BL-L324UEC	red	0.635	0.022	37.8	2500
BL-L324URC	ultra red	0.655	0.016	52.0	1800

$$I_v\text{[cd]} \rightarrow \Phi_v\text{, [lm]} \rightarrow s_{\text{LED}}(\lambda) \rightarrow \Phi_e\text{, [W]} \rightarrow \text{E}_e\text{, [W/m}^2\text{]} \rightarrow n_i^{max}\text{, [pcs.]} \rightarrow n_i^{on}/n_i^{off}\text{, [pcs.]}$$

where I_v – light intensity; Φ_v – phi is light flux; $s_{\text{LED}}(\lambda)$ – normalized spectral density of LED radiation power from changes in wavelength λ – lambda; Φ_e – phi – radiation power flow; E_e – radiance; n_i^{max} – the total number of LEDs in one luminaire for growing tomatoes and cucumbers; n_i^{on}/n_i^{off} – the required number of LEDs in the lamp in 'on' or 'off' mode to illuminate specific types of crops; i – LED type: Red, Green, Blue.

To recalculate radiation intensity into light flux, the following functional dependence is used (GOST 8.749-2011, 2015):

$$\Phi_v = \int I_v d\Omega,$$

where Φ_v – phi – light flux; I_v – light intensity; Ω – omega – solid angle, which depends on the area of the sphere part centred at the vertex of the angle, which is cut out by this solid angle, and the radius of the given sphere (Gurevich, 1983):

$$d\Omega = \frac{dS}{R^2},$$

where $d\Omega$ – omega – solid angle element expressed in intervals of linear angles of azimuth; dS – the area of the sphere part centred at the vertex of the angle, which is cut out by this solid angle; R – the radius of the given sphere.

The solid angle element for a spherical coordinate system is determined from the formula (Gurevich, 1983):

$$d\Omega = \frac{dS}{R^2} = \frac{R^2 \sin\theta d\theta d\varphi}{R^2} = \sin\theta d\theta d\varphi,$$

where $d\Omega$ – omega – solid angle element; dS – the area of a sphere part; R – radius of the sphere; θ – theta – linear angle of azimuth; dq – theta and $d\varphi$ – phi – intervals of linear angles of azimuth.

The LEDs used are isotropic sources. Their radiation field has a sufficiently high degree of symmetry and is circularly symmetric. The direction is chosen arbitrarily, with this choice of the coordinate system the intensity does not depend on the angle φ. Therefore, integration over φ in this case is reduced to multiplication by 2p (GOST 8.749-2011, 2015). The normalized spatial distribution of the radiation intensity of the types of LED used is approximated by the function $\cos^b(\theta)$, where θ – theta – linear angle of azimuth, with the parameter b=27, and the approximation error does not exceed ±5%. Then intensity of optical radiation depends only on the angle θ, and the following equation is valid for integration with it (GOST 8.749-2011, 2015):

$$\Phi_v = 2\pi\int_0^\alpha I_v(\theta)\sin(\theta)d\theta = 2\pi\int_0^\alpha I_{0v}\cos^b(\theta)\sin(\theta)d\theta = I_{0v}\frac{2\pi}{b+1}\left[1-\cos^{b+1}(\alpha)\right],$$

where Φ_v – phi – radiation light flux; I_v – spatial distribution of light intensity; θ – theta – linear angle of azimuth; I_{0v} – maximum value of light intensity at θ = 0º; dq – theta – increment interval of the linear azimuth angle; α – alpha – the half-angle of divergence, respectively, the total radiation angle is 2α; b – approximation parameter of the normalized spatial distribution of LED radiation intensity.

To determine the radiant flux of radiation, the light flux of radiation is absolutized based on the normalized spectral power density of LED and relative spectral luminous efficiency of monochromatic radiation for daytime vision (GOST 8.749-2011, 2015; Gurevich, 1983):

$$\Phi_e = \frac{\Phi_v}{K_m\int_{\lambda\min}^{\lambda\max} s_{\text{LED}}(\lambda)v(\lambda)d\lambda},$$

where Φ_e – phi – radiant flux of radiation; λ_{min} – lambda and λ_{max} – lambda – lower and upper limits of radiation spectrum, which are respectively 0.36 and 0.83 μm (GOST 8.749-2011, 2015); Φ_v – phi – light flux of radiation; $s_{\text{LED}}(\lambda)$ – normalized spectral power density of LED radiation from the change in wavelength λ – lambda; K_m – maximum light spectral efficiency corresponding to a wavelength of 0.555 μm for a standard photometric observer in daylight is 683 lm/W; ν(λ) – nu – relative spectral light efficiency of monochromatic radiation for daytime vision.

Energy illumination is calculated with the energy flux of radiation according to the following formula:

$$E_e = \frac{\Phi_e}{S} = \frac{\Phi_e}{\pi h^2 \tan^2(\alpha)},$$

where E_e – radiance; Φ_e – phi – radiation power flow; S – area of the illuminated surface; h –distance from the radiation source to the surface; α – alpha – angle of half-radiation brightness.

On the basis of the functional dependencies obtained above, taking into account the characteristics of the LEDs commercially produced by modern industry (see Table 1), layout of lighting systems (Bakharev, 2010; GOST 24940-96, 1997), current regulated intensity indicators from 150 to 300 W/m^2 (Departmental rules of the technological engineering NTP 10-95, 1996; Departmental rules of the technological engineering VNTP APK–19–07, 2007; Departmental rules of the technological engineering NTP APK 1.10.09.001-02, 2003) and spectral composition of greenhouse illumination (Tikhomirov et al., 2000; Bakharev et al., 2010), as well as the daily norm of the illumination of greenhouse crops (Tikhomirov et al., 2000) and statistical data on the dynamics of natural illumination level (not more than 90 W/m^2) (Lavrus, 1997) for the temperate continental climate zone in autumn-winter period, the mathematical model of the control process over modes of artificial supplementary lighting of greenhouse crops by measuring effective illumination in the visible optical range was further developed. As a result, dependence of dynamics of simultaneously activated types of LED modules was obtained (see Figure 3, number 2 – for cucumbers and Figure 3, number 4 – for tomatoes), depending on the time of day. Each module must be equipped with the following number of LEDs: Red – 12 pcs., Green – 18 and Blue – 10 pcs. Taking into account types of crops grown, the distribution of LEDs is established, which should be in 'on' or 'off' modes (see Figure 3, number 1 – for cucumbers and Figure 3, number 3 – for tomatoes). Thus, based on the results of the conducted research, the method of adaptive measuring control of illumination parameters of industrial greenhouses was substantiated (see Figure 4), which takes into account intensity, spectral composition and daily fluctuations of the combined effect of natural and artificial sources of radiation.

The main point of the proposed method is adapting operating modes of LED sources of greenhouse lighting (types and number of LEDs involved in the luminaire) based on the results of measuring effective radiance in the given spectral wavelength range to types and regimes of vegetation of the grown vegetable crops. The permissible error in measuring effective radiance in the visible optical wavelength range, which is found as the ratio of the relative spectral efficiency of photosynthesis obtained as a result of the use of LEDs and external illumination (see Figure 2, number 9) to the necessary relative spectral efficiency of photosynthesis (see Figure 2, number 8), the value of which should not exceed ±9%. Based on empirical data in the

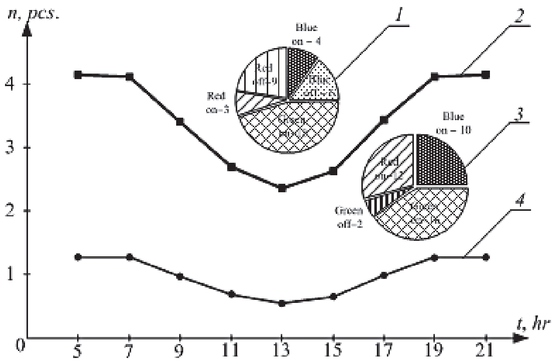

Fig. 3. Dynamics of changes in the number of LED modules required for the illumination of greenhouse crops: 1 – operation modes of LEDs in the module for cucumbers; 2 – number of modules for cucumber lightening; 3 – number of modules for supplementary illumination of tomatoes; 4 – operation modes of LEDs in the module for tomatoes

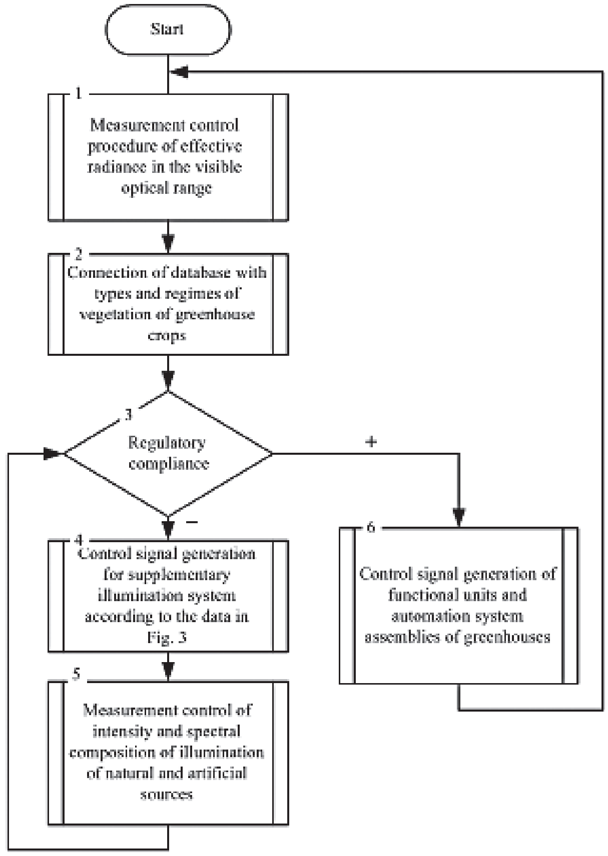

Fig. 4. Block diagram of the algorithm for adaptive control of effective radiance of industrial greenhouses in the visible optical range

field of vegetable growing under protected cultivation, given in (Theoretical substantiation of methods for increasing the cucumber yield in greenhouses, 1995) for cucumbers, taking into account the results of the studies carried out in this article, we can hypothetically assume that the increase in potential yield will be from 50 to 100%. This effect is achieved by increasing the coefficient of use of photosynthetic active radiation (Theoretical substantiation of methods for increasing the cucumber yield in greenhouses, 1995).

Discussion

To confirm the adequacy of the implementation of the development on the yield indicators of greenhouse crops, it is necessary to conduct research in the following priority areas:

✓ establishment of regularities of mutual influence of physicochemical parameters of the microclimate of greenhouses on the indices of the efficiency of plants under protected cultivation;

✓ experimental research in real conditions of information measuring devices on the basis of the proposed physical and mathematical models of processes occurring in artificial ecosystems;

✓ accumulation of statistical data and on their basis making models of predicting dynamics of informative parameters of greenhouse microclimate, taking into account destabilizing factors;

✓ development of methods and means for automatic control of technological processes for growing introduced crops under protected cultivation.

Conclusions

Scientific theoretical and practical foundations for increasing productivity of industrial greenhouse complexes due to justification of the method and structural algorithmic organization of the device for adaptive measurement monitoring and control of effective illumination in the visible optical wavelength range were studied, developed and substantiated. The mathematical model of the process of measuring and adjusting effective radiance of greenhouse complexes was further developed. The component base of the system for supplementary illumination of introduced flora is substantiated, which covers 91% of spectral distribution of relative efficiency of photosynthesis. The method of adaptive control of supplementary illumination modes of greenhouse crops was proposed based on the results of measuring illumination in a fixed spectral range, taking into account types and periods of vegetation of plants. The permissible error in measuring effective radiance in the given spectral range of wave lengths was estimated, which should not exceed ±9%. As a result of the studies, possible directions for further research on increasing efficiency of AIC facilities for protected cultivation are substantiated.

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