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Mathematical model for monitoring carbon dioxide concentration in industrial greenhouses

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Abstract. Processes of monitoring and control the industrial greenhouses microclimate play a decisive role in growing crops under protected cultivation. Providing optimal climatic conditions in the production process of greenhouse agricultural products requires solving the scientific and applied problem of developing and researching a mathematical model for monitoring carbon dioxide concentration in industrial greenhouses. The proposed model takes into account the processes of diffusion and absorption of carbon dioxide, the geometric parameters of greenhouses, as well as the types and vegetation periods of crops grown under protected cultivation. Time characteristics of the carbon dioxide dynamics process under greenhouse conditions are estimated. Quantitative estimates of the diffusion transfer duration and carbon dioxide absorption are made for indeterminate varieties of tomatoes during planting and fruiting periods. Recommendations are given on the development of an adaptive methodology for the functioning and structural and algorithmic organization of computerized monitoring and management system for carbon dioxide top-dressing modes for greenhouse crops. The necessity of improving the proposed mathematical model and confirming the adequacy of its implementation efficiency on yield indicators of greenhouse crops is substantiated.

Key words: modeling, mass transfer, photosynthesis, dynamics.

INTRODUCTION

The key to the state social and economic development is a high level of food security. The need to ensure the production of a sufficient amount of environmentally friendly products, as well as the climatic and structural and sectoral features of the state development, raise attention to the production of crop products under protected cultivation. A promising area for increasing the efficiency of agro-industrial complex facilities is the modernization of industrial greenhouses through the development and implementation of modern computerized infocommunication monitoring and management tools for growing the greenhouse flora.

Having analyzed the greenhouse parameters as objects of control and monitoring, it is established that the development of climate controllers operation algorithms is a science-intensive and non-standard procedure. For optimal control of the greenhouse crops growing processes, mathematical physics equations are used. They describe the dynamic processes of mass and energy balance taking into account the processes of diffusion and convection.

One of the main physico-chemical parameters of the industrial greenhouses microclimate, which affects the rates of growth and production of growing crops, is the concentration of carbon dioxide (CO_2) (Katsoulas & Kittas, 2008; Santosh et al., 2017).

In the process of analysis of research results in the field of vegetable growing under protected cultivation (Theoretical substantiation of methods for increasing the cucumber yield in greenhouses, 1995) established fact of the correlation dependence between the productivity of growing cucumbers and the current concentration of carbon dioxide in greenhouses. It was found that a change in the concentration from 0.03% to 0.2% leads to a proportional increase in productiveness. The optimal concentration of CO_2 depending on the types of plants grown and the periods of their vegetation varies from 0.05 to 0.2% (Departmental rules of the technological engineering NTP 10-95, 1996; Departmental rules of the technological engineering VNTP APK–19–07, 2007). This fact confirms the relevance of the research for different types of crops and the periods of their vegetation.

The technological characteristics of the existing control and monitoring systems for the carbon dioxide concentration in industrial greenhouses claimed by the manufacturers (OX-AN, 2017; TechGrow CO_2-controllers, 2017) do not allow us to assess adequately the possibility of adapting these systems for different types of crops and greenhouse structures. This drawback is due to the lack of open access to the description of the principles of the industrial climate controllers operation for greenhouses.

The analysis of existing software products of the type (Greentrees Hydroponics CO_2 Calculator, 2017) for calculating the CO_2 concentration required for greenhouse plants top-dressing has made it possible to establish their notable drawback. It lies in the absence of a description of the algorithms for their functioning, which makes it difficult to objectively analyze the results.

This limits the possibility of using this type of software for adaptive calculating the optimum concentration of carbon dioxide, taking into account the geometric parameters of the greenhouses and the types of crops grown.

Thus, there arises the need to solve the scientific and applied problem of developing a mathematical model for the process of the dynamics of the carbon dioxide concentration in conditions of growing crops under protected cultivation, considering the geometric characteristics of greenhouses, as well as the types and periods of plants vegetation. This will make it possible to create an adaptive system for monitoring and controlling the microclimate of greenhouses and give recommendations on increasing the yield of industrial greenhouse complexes.

The subject of the article is the mathematical model and the corresponding adaptive technique for increasing the efficiency of the functioning of computerized monitoring and control systems for the carbon dioxide top-dressing of greenhouse flora.

The aim of the research is to develop and study the mathematical model of the process of carbon dioxide dynamics under greenhouse conditions to develop scientific and theoretical positions and to carry out practical research on the structural and algorithmic organization of computerized systems for monitoring and controlling the concentration of carbon dioxide. This will increase the efficiency of agro-industrial vegetable crop complexes functioning under protected cultivation.

MATERIALS AND METHODS

In the course of the research, the authors have developed the model for monitoring the carbon dioxide concentration in industrial greenhouses by applying physical and mathematical modeling methods and modern software packages NI LabView and Mathcad. Wireless information exchange is implemented by using the RemoteXY service. Principles of functioning of this service correspond to the concept of Internet of Things and described in detail in the literature source (RemoteXY, 2017). Values of the coefficients in the CO_2 dynamics equation under conditions of industrial greenhouses have been obtained by analyzing scientific sources (Koshkin & Shirkevich, 1976; Carbon Dioxide In Greenhouses, 2017; Gas exchange in greenhouses, 2017), as well as by laboratory testing of the developed hardware and software of the automated greenhouse physical model (Vovna et al., 2016; Laktionov et al., 2017b) (see Fig. 1, a, b), which takes into account the condition of geometric similarity to real industrial greenhouses (ratio of height (h): length of base (a): width of base (b) is 1: 1: 0.6), followed by regression analysis of empirical data. The dimensions of the implemented physical model of the greenhouse are the following: h = 1.5 m, a = 1.5 m, b = 0.9 m.

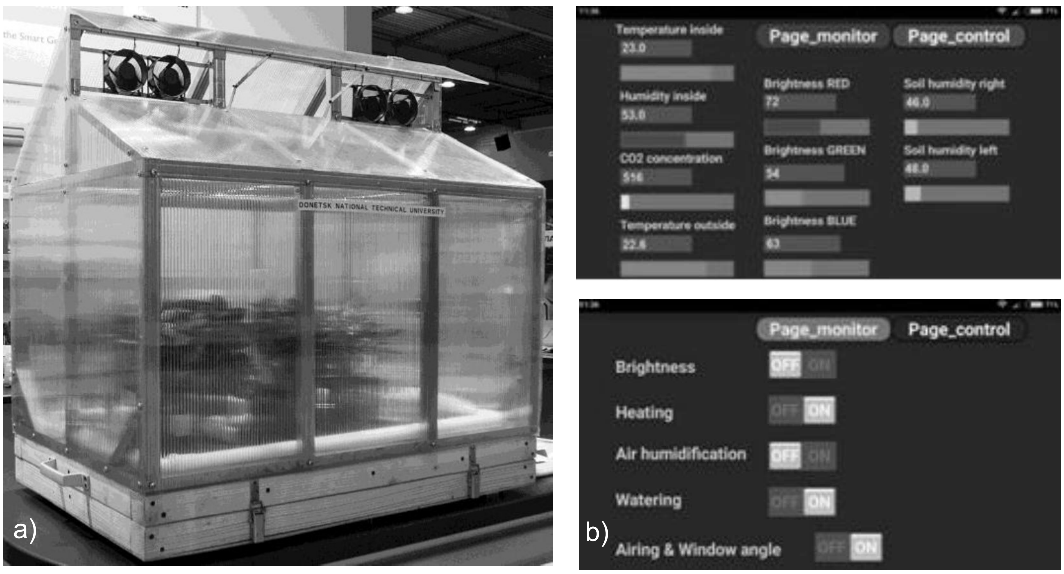

Figure 1. Hardware-software implementation of the automated physical model of a greenhouse: a) external view of the physical model of an automated greenhouse; b) interface of the software component of the monitoring and control system.

The measuring channel for the carbon dioxide concentration is a structural component of the system for monitoring and controlling the parameters of the industrial greenhouses microclimate (Laktionov et al., 2017a). It is based on the MG-811 sensor which is compatible with the Arduino Mega microprocessor platform characterized by the basic relative error of ± 0.3% with a dynamic measuring range of 350 to 10,000 ppm.

Simulation of the process of carbon dioxide dynamics for industrial greenhouses was carried out under the following conditions, which are shown in Table 1.

Table 1. Modeling conditions

Condition type	Accepted restriction
The concentration of carbon dioxide in the source area at the initial moment of time	$C_{CO_2}(0,0)$= 0.3%
The concentration of carbon dioxide at the base of the greenhouse at the initial moment of time	$C_{CO_2}(H,0)$= 0.15%
The optimal level of carbon dioxide concentration for top-dressing, which is measured in the greenhouse at the initial time	C_{max}= 0.2%
Coefficient of carbon dioxide molecular diffusion	$D_{CO_2} = 0.14 \cdot 10^{-4}$ m^2 s^{-1}
Type of greenhouse	Vegetable, year-round use, hangar
Greenhouse material	Honeycomb polycarbonate
Height of the greenhouse	H = 4 m
Study period	T = 1 hour
Coordinates of the carbon dioxide dynamics *Z* (distance from the gas source to the location of the cultivated crops)	Z_1 = 3.7 (height of the tomato shrub in the planting period h = 0.3 m); Z_2 = 2.8 (the height of the tomato shrub in the fruiting period h = 1.2 m)
Imposed constraints	Isothermal process; convective mass transfer of CO_2 is absent
Types of plants grown	Indeterminate varieties of tomatoes

As a basic technology for carbon dioxide top-dressing of greenhouse plants, a system of supplying pure (liquefied) carbon dioxide using small diameter pipes was used to construct a mathematical model for monitoring the CO_2 concentration in industrial greenhouses (see Fig. 2). This technology was chosen on the basis of a comparative analysis of technical characteristics of existing engineering solutions for agronomic tasks of top-dressing greenhouse plants with carbon dioxide (Lotonov & Iuferev, 2012; Consideration of the main factors in modeling vegetable production in the greenhouse, 2017).

This technology allows performing accurate and economical automatic dosing of carbon dioxide taking into account the daily dynamics of the photosynthetic process, regulating the distance from the CO_2 source to plants, and evenly distributing the gas in the greenhouse volume. However, the claimed type of systems has a number of technological imperfections associated with the limited research results on the regularities of the optimal CO_2 flow depending on the types of plants grown and the periods of their vegetation, which leads to the lack of algorithms for adaptive management of the process of top-dressing plants with carbon dioxide.

Thus, to justify adaptive algorithms for the operation of automatic carbon dioxide top-dressing systems for plants on the basis of climate controllers in industrial greenhouses, the scientific and technical task of developing a mathematical model for the process of monitoring the carbon dioxide concentration arises.

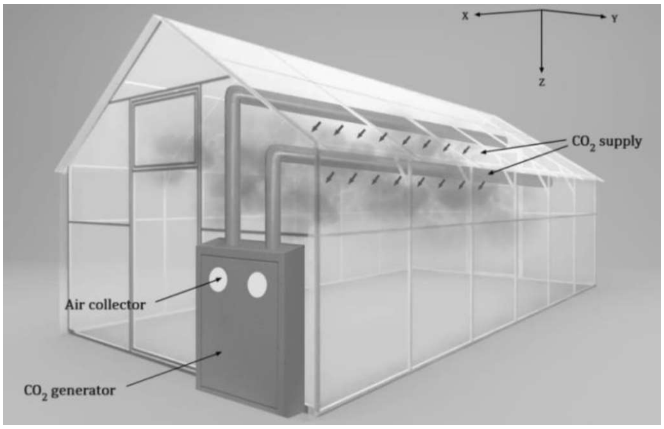

Figure 2. Technological scheme of top-dressing plants with CO_2 using small diameter pipes.

The results of the research were obtained during the implementation of the research in the State Higher Educational Establishment 'Donetsk National Technical University': 'Development of methods and means for increasing the efficiency of computerized information and measuring systems of technological processes' and 'Development of intelligent measuring modules for electronic systems for monitoring physical parameters of physical media'. The results were also piloted at the XXI International Exhibition elcomUkraine (Kiev, Ukraine, 2017).

RESULTS AND DISCUSSION

The mathematical model of the process of monitoring carbon dioxide concentration in industrial greenhouses is based on the balance equation of mass (Hashimoto & Day, 1991):

$$\varphi_{CO_2}^{sour} - \varphi_{CO_2}^{vent} - \varphi_{CO_2}^{phot} = 0 \quad (1)$$

where $\varphi_{CO_2}^{sour}$ is the amount of carbon dioxide entering the greenhouse; $\varphi_{CO_2}^{vent}$ is the amount of carbon dioxide removed from the greenhouse by means of ventilation; $\varphi_{CO_2}^{phot}$ is the amount of carbon dioxide consumed by plants as a result of the photosynthesis process.

The distribution of carbon dioxide in the greenhouse volume takes place under the influence of two processes, one of which is molecular diffusion, that is, the movement of CO_2 molecules in the direction opposite to the concentration gradient. The other is the molecules transport as a result of the air currents motion (convection). As a rule, these processes occur simultaneously.

Thus, considering the Eq. (1) for the isothermal case, the equation of carbon dioxide convective diffusion (Shervud et al., 1982; Kashirskaya et al., 2008; Parfenteva et al., 2013) under the conditions of industrial greenhouses for the Cartesian coordinate system is as follows:

$$\frac{\partial C_{CO_2}}{\partial t} = D_{CO_2}\left(\frac{\partial^2 C_{CO_2}}{\partial x^2} + \frac{\partial^2 C_{CO_2}}{\partial y^2} + \frac{\partial^2 C_{CO_2}}{\partial z^2}\right) - \underbrace{\left(\overrightarrow{V_x}\frac{\partial C_{CO_2}}{\partial x} + \overrightarrow{V_y}\frac{\partial C_{CO_2}}{\partial y} + \overrightarrow{V_z}\frac{\partial C_{CO_2}}{\partial z}\right)}_{\varphi_{CO_2}^{vent}} + \quad (2)$$

$$+\varphi_{CO_2}^{sour}(x,y,z,t) - \varphi_{CO_2}^{phot}(x,y,z,t)$$

where C_{CO_2} is carbon dioxide concentration; D_{CO_2} is the coefficient of carbon dioxide molecular diffusion; $\overrightarrow{V_x}$, $\overrightarrow{V_y}$, $\overrightarrow{V_z}$ is the air currents velocity along the corresponding coordinates; $\varphi_{CO_2}^{sour}$ is the amount of carbon dioxide entering the greenhouse from the source; $\varphi_{CO_2}^{phot}$ is the amount of carbon dioxide consumed by plants as a result of photosynthesis.

Having analyzed the technological scheme for top dressing of greenhouse plants with carbon dioxide, shown in Fig. 2, as well as the physicochemical properties of carbon dioxide, it is assumed that the intensity of the change in the carbon dioxide concentration in the coordinate (z) is much greater in comparison with the coordinates *x* and *y*, since CO_2 is heavier than air. This leads to its settling in the direction of the (z) coordinate (see Fig. 2). The technological scheme of top-dressing plants with CO_2 is constructed in such a way that the concentration gradient in the (x) and (y) direction can be zero, taking into account the assumption regarding the absence of convective gas transfer ($\frac{\partial^2 C_{CO_2}}{\partial x^2} = 0$, $\frac{\partial^2 C_{CO_2}}{\partial y^2} = 0$).

The solution of the problem of constructing and analyzing the mathematical model of the process of carbon dioxide dynamics under industrial greenhouse conditions, which in general is described by the Eq. (2), can be obtained by using the source method (Source method (impulse method), 2017). The physical meaning of this method is to generate a concentration field of the diffusing substance, in this case CO_2, which is formed by diffusant point sources distributed in space and time (Mors & Feshbakh, 1960).

When compiling a differential equation that describes the processes of carbon dioxide emission and absorption under greenhouse conditions, the restriction on the process of convective gas transfer is introduced. This process is caused by the ventilation of the greenhouses. In this case, we will consider the greenhouse to be a closed system, and there is no convective component of carbon dioxide mass transfer, because in scientific sources there is no up-to-date information on the quantitative characteristics of its effect on the dynamics of carbon dioxide. To take into account the process of convective carbon dioxide transport, additional experimental studies are required.

Thus, the problem in question can be formulated as follows: the greenhouse is a closed system in which the processes of carbon dioxide emission by point sources take place, with the initial distribution of the $C_{CO_2}(0)$ concentration and the boundary conditions $C_{CO_2}(0,t) = C_1$ and $C_{CO_2}(H,t) = C_2$; at the initial time in the greenhouse the required level of carbon dioxide concentration $C_{CO_2}(0) = C_{max}$, is reached, and the sources of the diffusant are switched off ($\varphi_{CO_2}^{sour}(x, y, z, t) = 0$); convective mass transfer of carbon dioxide is absent ($\varphi_{CO_2}^{vent}(x, y, z, t) = 0$); when analyzing the dynamics of CO_2 in the greenhouse, gas is absorbed by plants with uniform density; the estimated value of the intensity of CO_2 absorption by plants (Carbon Dioxide In Greenhouses, 2017; Gas exchange in greenhouses, 2017) remains constant in space and time, but depends only on the types of crops grown. Current results of researches in the field of quantitative estimates of an indicator intensity of CO_2 absorption of various types of plants are rather limited. Possible ranges of intensity change of photosynthesis depending on the area of leaves of the grown-up cultures are specified in literature sources (BiologyGuide, 2017; Vegetables growing in hydroponic greenhouses, 2017). This parameter can be determined by authors' algorithm which is presented in the flow-chart form in Fig. 3 as a result of researches. The value for early ripening indeterminate varieties of tomatoes is equal: $\varphi_{CO_2}^{phot} = 27$ mg dm^{-3} h^{-1}.

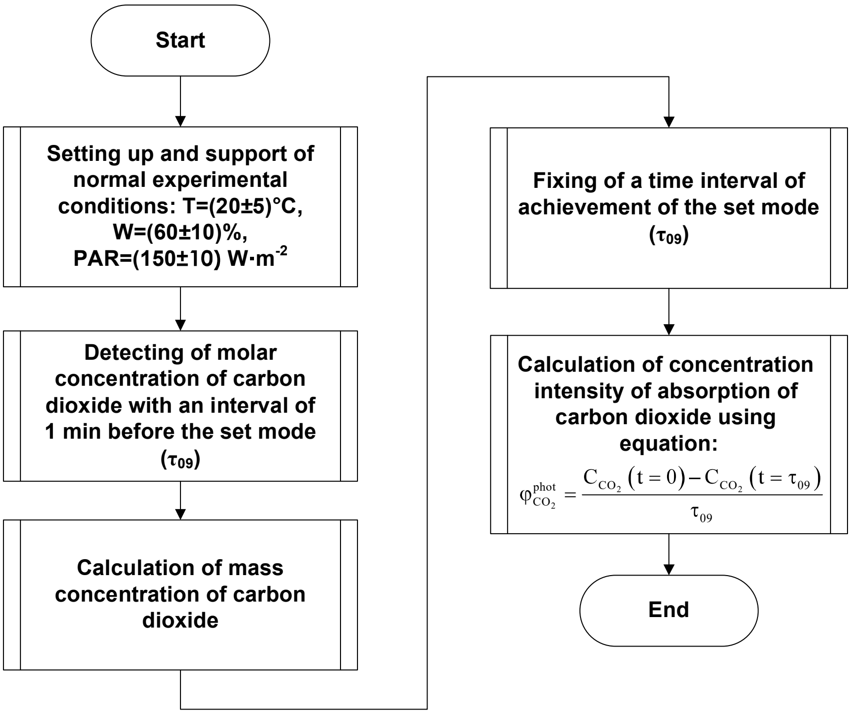

Figure 3. Flow-chart form of algorithm of calculation of CO_2 absorption intensity (T – temperature of the air; W – humidity of the air; E – efficient lighting of crop growing area in the visible light range; τ_{09} – the time to reach steady-state process).

Based on the analysis of the above processes of carbon dioxide dynamics in industrial greenhouses, the differential equation for the problem under consideration is as follows:

$$\frac{\partial C_{CO_2}}{\partial t} = D_{CO_2} \frac{\partial^2 C_{CO_2}}{\partial z^2} - \varphi_{CO_2}^{phot}. \quad (3)$$

The differential Eq. (3) while using the Green's function method (Mikhailova & Domanova, 2012; Source method (impulse method), 2017) in general form can be solved through the following expression:

$$C_{CO_2}(z,t) = f_1(z) + f_2(z,t) - f_3(z,t), \tag{4}$$

where $f_1(z)$ is the function taking into account the initial distribution of CO_2 concentrations in the greenhouse under zero boundary conditions and the absence of gas consumption; $f_2(z,t)$ is the function taking into account the boundary conditions for the distribution of CO_2 in the greenhouse under zero initial conditions and the absence of gas consumption; $f_3(z,t)$ is the function taking into account gas consumption by plants in the process of photosynthesis with zero initial and boundary conditions.

Thus, the function $f_1(z)$ in Eq. (4) is a solution for the stationary state of carbon dioxide diffusion in greenhouse conditions, i. e. solution to the equation of the form $\frac{\partial^2 C_{CO_2}}{\partial z^2} = 0$ under boundary conditions $f_1''(z) = 0$, $f_1(0) = C_1$, $f_1(H) = C_2$:

$$f_1(z) = C_1 + \frac{z}{H}(C_2 - C_1), \tag{5}$$

where C_1 and C_2 are the boundary concentrations of carbon dioxide at the gas source points and in the plant area, respectively; H is the distance from the source of gas to the plant beds; z is the integration variable (coordinate).

Function $f_2(z, t)$ is the solution for the non-stationary case:

$$\frac{\partial f_2}{\partial t} = D_{CO_2} \cdot \frac{\partial^2 f_2}{\partial z^2}, \tag{6}$$

under simple boundary conditions $f_2(z,0)=C_{max}-f_1(z)$.

Based on the analysis of literature sources (Lykov, 1967; Carbon Dioxide In Greenhouses, 2017; Source method (impulse method), 2017) concerning non-stationary differential equations of mathematical physics, the differential Eq. (6) is solved:

$$\begin{aligned} f_2(z,t) = {} & \frac{2}{\pi}\sum_{n=1}^{\infty}\left[\left(\frac{C_2 \cdot \cos(n\pi) - C_1}{n\pi}\right) \cdot \sin\left(\frac{n\pi z}{H}\right) \cdot e^{-\frac{n^2\pi^2 D_{CO_2} t}{H^2}}\right] + \\ & + \frac{4}{\pi} C_{max} \sum_{k=0}^{\infty} \frac{1}{2k+1} \cdot \sin\left(\frac{(2k+1)\pi z}{H}\right) \cdot e^{-\frac{(2k+1)^2 \pi^2 D_{CO_2} t}{H^2}} \end{aligned}, \tag{7}$$

where C_1 and C_2 are the boundary concentrations of carbon dioxide at the gas source points and in the plant area, respectively; n, k are the serial numbers of the pulse obtained as a result of multiple reflections of CO_2 molecules from the walls of the greenhouse; H is the distance from the source of gas to the plant beds (approximately equal to the height of the greenhouse); C_{max} is the required carbon dioxide concentration level diagnosed in the greenhouse at the initial time; D_{CO_2} is the required carbon dioxide concentration, which is diagnosed in the greenhouse at the initial time; z, t are the integration variables, respectively, coordinate and time.

The function $f_3(z,t)$ in the Eq. (4) takes into account the gas consumed by plants in the process of photosynthesis under zero initial and boundary conditions. It is considered that the value of the CO_2 absorption by plants does not depend on the coordinate (z) and time (t). The function was obtained by analyzing general form of the equations of mathematical physics, given in specialized sources (Lykov, 1967; Source method (impulse method), 2017) and has the following form:

$$f_3(z,t)=\frac{4H^2\varphi_{CO_2}^{phot}}{\pi^3 D_{CO_2}}\sum_{n=0}^{\infty}\left(\frac{1}{(2k+1)^3}\cdot\sin\left(\frac{2k+1}{H}\cdot z\right)\cdot\left(1-e^{-\frac{(2k+1)^2 n^2 D_{CO_2} t}{H^2}}\right)\right), \qquad (8)$$

where H is the distance from the source of gas to the plants beds; $\varphi_{CO_2}^{phot}$ is the intensity of CO_2 absorption by plants; D_{CO_2} is the coefficient of carbon dioxide molecular diffusion; n, k are the serial numbers of the pulse obtained as a result of multiple reflections of CO_2 molecules from the walls of the greenhouse (in this case, the main impulse is considered k = 1); z, t are the integration variables, respectively, coordinate and time.

Thus, by substituting the solutions (5), (7) and (8) into the Eq. (4), the mathematical model describing the processes of carbon dioxide dynamics under the technological conditions of growing crops on sheltered grounds is obtained:

$$\begin{aligned}C_{CO_2}(z,t)=&\underbrace{\left\{C_1+\frac{z}{H}(C_2-C_1)\right\}}_{f_1(z)}+\\&+\left\{\underbrace{\begin{aligned}&\frac{2}{\pi}\sum_{n=1}^{\infty}\left[\left(\frac{C_2\cdot\cos(n\pi)-C_1}{n\pi}\right)\cdot\sin\left(\frac{n\pi z}{H}\right)\cdot e^{-\frac{n^2\pi^2 D_{CO_2} t}{H^2}}\right]+\\&+\frac{4}{\pi}C_{max}\sum_{k=0}^{\infty}\frac{1}{2k+1}\cdot\sin\left(\frac{(2k+1)\pi z}{H}\right)\cdot e^{-\frac{(2k+1)^2\pi^2 D_{CO_2} t}{H^2}}\end{aligned}}_{f_2(z,t)}\right\}+\\&+\left\{\underbrace{-\frac{4H^2\varphi_{CO_2}^{phot}}{\pi^3 D_{CO_2}}\sum_{n=0}^{\infty}\left(\frac{1}{(2k+1)^3}\cdot\sin\left(\frac{2k+1}{H}\cdot z\right)\cdot\left(1-e^{-\frac{(2k+1)^2 n^2 D_{CO_2} t}{H^2}}\right)\right)}_{f_3(z,t)}\right\},\end{aligned} \qquad (9)$$

Based on the developed mathematical model of the carbon dioxide monitoring process under industrial greenhouse conditions (9), taking into account the required CO_2 concentration for efficient photosynthesis for the varieties of tomatoes in question and its gradient in a closed volume, the normalized characteristics of the CO_2 dynamics were obtained (Carbon Dioxide In Greenhouses, 2017; Increasing the productivity of greenhouse farms by using the emissions of contact water heaters, 2017) (see Fig. 4) under the conditions described above.

The qualitative analysis of the parameters in Fig. 4 can be used to construct adaptive algorithms for the functioning of phytocontrollers. The essence of the proposed methodology is to adapt the operating modes of monitoring and control systems for fertilizing plants with carbon dioxide as measured by the current CO_2 concentration in real time, depending on the parameters z – plant height (indirectly takes into account the vegetation period) and $\varphi_{CO_2}^{phot}$ – CO_2 absorption intensity (indirectly takes into account the type of crops).

The quantitative analysis of the results of modeling the process of carbon dioxide dynamics in industrial greenhouses, which are shown in Fig. 4, reveals that within an hour, the concentration of CO_2 decreases from the initially established level by 6% for indeterminate varieties of tomatoes during the fruiting period and by 2% during the planting period. It has also been established that the process of CO_2 dynamics in greenhouses can be divided into three characteristic stages: 1 – sharp decline in the parameter (no more than 1–2 min) is due to a significant predominance of the photosynthetic process over the CO_2 diffusion at the initial moment of time at the height of plants; 2 – linear decline in the parameter (approximately 25 min – for crops during the period of planting, 55 min – for crops in the period of fruiting) is due to the predominance of the process of photosynthesis over CO_2 diffusion; 3 – the steady process (starting from 25 minutes – for crops during the period of planting, from 55 minutes – during the fruiting period) is due to the balancing of competing processes of diffusion and CO_2 absorption by plants.

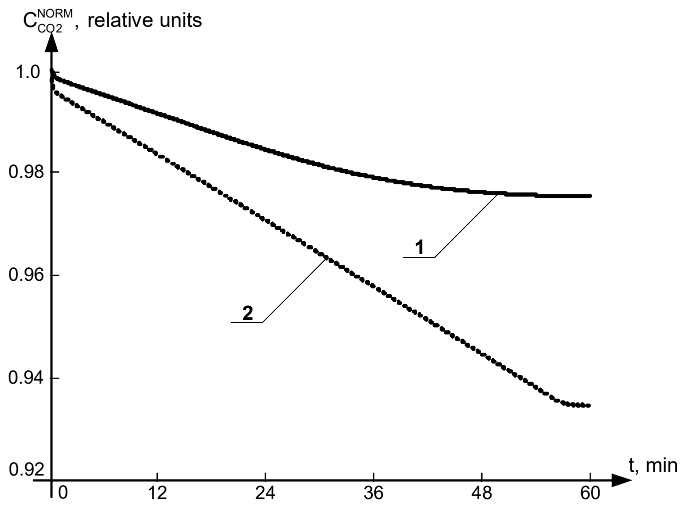

Figure 4. Results of modeling the carbon dioxide dynamics in industrial greenhouses (1 – for indeterminate varieties of tomatoes in the period of planting, h = 0.3 m; 2 – for indeterminate varieties of tomatoes during fruiting, h = 1.2 m).

Thus, the developed mathematical model of the process of carbon dioxide dynamics under greenhouse conditions has allowed developing scientific and theoretical provisions on the structural and algorithmic organization of computerized systems for monitoring and controlling the concentration of carbon dioxide. In future this will improve the efficiency of the agro-industrial objects for growing vegetable crops on sheltered grounds. To improve the proposed mathematical model and confirm the adequacy of its implementation in the yield indicators of greenhouse crops, it is necessary to conduct comprehensive studies on establishing the regularities in the influence of CO_2 convective mass transfer on the process of crops photosynthesis under real conditions of industrial greenhouses.

A structural diagram of the system for automatic regulation of carbon dioxide concentration for industrial greenhouses based on the developed mathematical model is shown in Fig. 5.

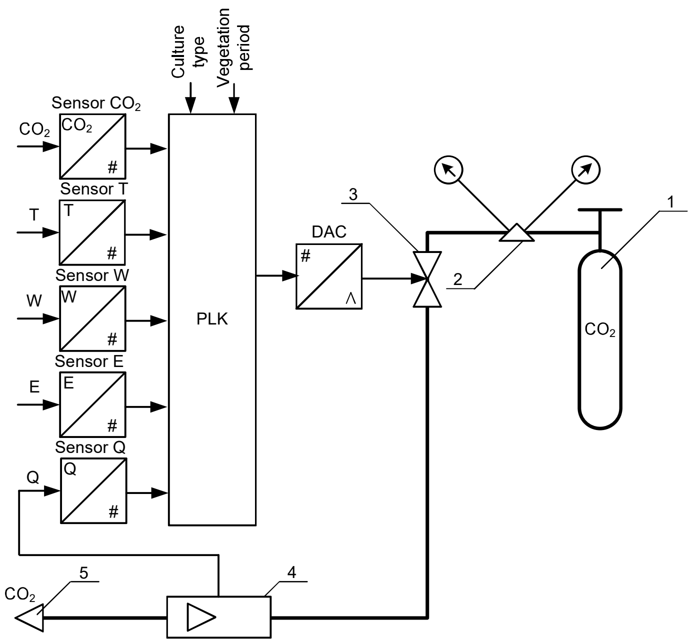

Figure 5. Structural diagram of the automatic regulation system of CO_2 concentration for industrial greenhouses (1 – cylinders with carbon dioxide; 2 – reducer; 3 – regulation valve with solenoid flap; 4 – rotameter; 5 – carbon dioxide collection in the ventilation system of industrial greenhouses).

The digital sensors placed in the industrial greenhouse carry out measurements of carbon dioxide concentration in crop growing area (sensor CO_2), temperature of the air (sensor T), humidity of the air (sensor W) and efficient lighting of crop growing area in the visible light range with due regard to circadian dynamics of the natural light (sensor E). Information from the sensors outputs comes to the controller (PLK) where the necessary volume of carbon dioxide for feeding up the grown-up cultures calculates using developed algorithms taking into account their types and current vegetation periods.

Carbon dioxide from cylinders (see Fig. 5) arrives through a reducer on the regulation valve. Smooth regulation by the electromagnetic flap of the valve of supply of carbon dioxide from cylinders carried out from PLK via the digital-to-analog converter (DAC). Carbon dioxide arrives on the rotameter which defines its volume expense after the regulation valve. In the developed system of automatic control injected the feedback on a volume flow for decreasing of an overshoot error. Information about this parameter entered into PLK using a digital flow-rate sensor (sensor Q). Carbon dioxide dumped into the ventilation system of the industrial greenhouse after the rotameter.

The developed diagram realizes the offered mathematical model. It will allow confirming efficiency development introduction on indicators of productivity of greenhouse cultures when carrying out complex researches on establishment of influence's regularities of a convective carbon dioxide mass transfer on process of cultures photosynthesis in actual operating conditions.

CONCLUSIONS

The article studies the development of scientific, theoretical and practical foundations for increasing the productivity of industrial greenhouse complexes by justifying the mathematical model for monitoring the carbon dioxide concentration in industrial greenhouses. The developed mathematical model is an analytical solution of the differential equation of the carbon dioxide mass balance, which takes into account the diffusion and absorption of carbon dioxide, the geometric parameters of the greenhouses, and the types and periods of vegetation of crops grown under protected cultivation.

The main stages and time characteristics of the process of carbon dioxide dynamics under greenhouse conditions are defined. Quantitative estimates of the duration of diffusion transfer and carbon dioxide absorption periods are established for indeterminate varieties of tomatoes during the period of planting and fruiting.

Based on the analysis of modeling results, recommendations are given on the development of an adaptive methodology for the functioning, as well as structural and algorithmic organization of the computerized monitoring and management system for the top-dressing of greenhouse crops with carbon dioxide.

The necessity to improve the proposed mathematical model and confirm the adequacy of its implementation effectiveness on the yield indicators of greenhouse crops is substantiated by carrying out complex studies on establishing the regularities of the influence of carbon dioxide convective mass transfer on the process of crops photosynthesis under real conditions of industrial greenhouses.

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