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Implementation of the developed models and algorithms in problems of control of the process of culturing of chlorella

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Abstract. The article considers the implementation of mathematical models and algorithms for hanging the efficiency of managing the chlorella cultivation process on the basis of the modeling algorithm of state parameters. One of the necessary conditions for the optimal conduct of the process of cultivating microorganisms is automatic control of the quality and composition of nutrients at the inlet, as well as control of the output indicators of the process. Based on the results of theoretical and experimental studies performed using modern methods and tools, as well as the positive results of industrial tests, it is possible to increase the efficiency of controlling the chlorella cultivation process on the basis of a modeling algorithm for state parameters.

1. Introduction

The developed models, control algorithms, software and hardware and a flexible configuration control system for the chlorella growth process allow predicting production situations and technological conditions with a sufficient degree of accuracy, optimizing the process mode, and improving the accuracy of control and management. The proposed and justified repeated use of seed crops provides an opportunity to improve the quality and increase the output of target products while reducing the consumed nutrients and energy resources, reduce losses and improve the culture of service and reduce the number of service personnel [6, 7, 8, 9].

2. Research methodology

The model of the technological process of cultivating chlorella is an approximate description of the complex mechanism of enzymatic transformations and the development of various nutrients (N, P, K, Mg, CO₂, etc.) necessary for the growth and reproduction of chlorella [1,2,3,4,20,21,22, 23].

As a result, we obtain the following system of equations:



$$\left\{ \begin{array}{l} \frac{dx}{dt} = \mu x; \\ \frac{dS_{P_i}^i}{dt} = d_\varepsilon \mu x; \\ \frac{dS_{m_i}^i}{dt} = m_\varepsilon x; \\ \mu = \mu_m \frac{S_i}{K_{S_i}} \exp \left[\frac{(pH - \varphi_1)^2}{\delta_1^2} - \frac{(T - \varphi_2)^2}{\delta_2^2} - \frac{(C - \varphi_3)^2}{\delta_3^2} \right]; \\ \frac{ds}{dt} = (\alpha_1 \mu + m_i) x \end{array} \right. \quad (1)$$

Thus, the resulting system of equations (1) describes the process of cultivating chlorella, implemented in a periodic mode. When the set value X is reached, the process is transferred to a continuous mode in order to increase the productivity of cultivators and stable use, crops and nutrients. This model can be represented as a homomorphic one, developed under certain assumptions [15,16,17].

Thus, on the basis of the obtained kinematic equations and control of the hydrodynamic structure of flows in the reactor, we compose the following generalized mathematical model of the microalgae cultivation process:

$$\left\{ \begin{array}{l} \frac{dx_i}{dt} = \frac{V}{v_i} (x_{i-1} - x_i) + \mu_i x_i \\ \frac{dSp_{ij}}{dt} = \frac{V}{v_i} (Sp_{i-1,j} - Sp_{i,j}) - \alpha_i \mu_i x_i \\ \frac{dSm_{ij}}{dt} = \frac{V}{v_i} (Sm_{i-1,j} - Sm_{i,j}) - \mu_i x_i \\ \mu_i = \mu_m \frac{S_{ij}}{K_{S_i} + S_{ij}} \exp \left[-\frac{(ph - \varphi_1)^2}{\sigma_1^2} - \frac{(T - \varphi_2)^2}{\sigma_2^2} - \frac{(l - \varphi_3)^2}{\sigma_3^2} \right] \\ \frac{dS_{ij}}{dt} = \frac{V}{v_i} (S_{i-1,j} - S_{i,j}) - (\alpha \mu_i + m) x_i \end{array} \right. \quad (2)$$

The next task is to determine the values of the coefficients included in the equation.

Before using the resulting model with parameters determined on the basis of parametric identification procedures, its adequacy to real processes.

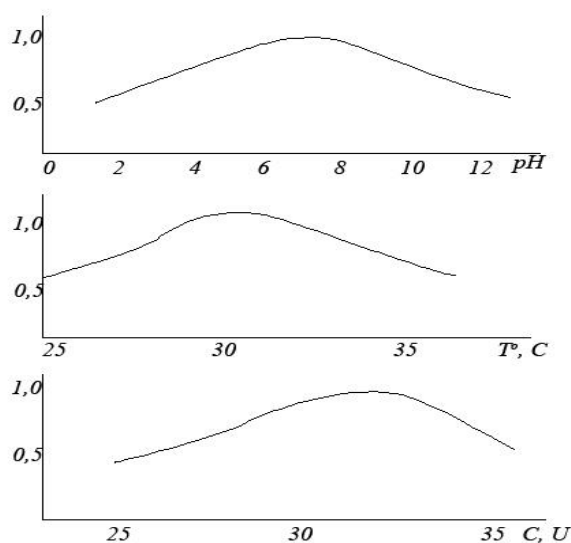


Figure 1. Dependences of μ on pH,T,C: α - μ on pH; β - μ on T; β - μ on C.

Only after that it is possible to simulate and study various modes on a computer and develop specific recommendations for technologists on the optimal conduct of the process, use the resulting models to solve optimization problems, as well as for a reasonable synthesis of control systems. For this purpose, we carried out experimental studies aimed at determining the values of the coefficients and regime parameters of the object under study [11,13].

On fig. 1. The calculated and experimental data are presented, reflecting the main indicators of the cultivation of chlorella in the periodic mode of the process. Comparison of the results obtained on the basis of theoretical calculations by solving systems of equations (2) with experimental data correlated with the requirements of the technological regulations showed that the calculated data coincide with the experimental ones with an accuracy of 5-7%. Here it is appropriate to note that for the class of objects under consideration, the experimental determination of the amount of substances converted or used for growth and reproduction (N, P, K, Mg, CO₂, etc.) is a rather difficult task, and in some cases it even practically unresolved. Meanwhile, the proposed process model, presented in the form of a system of equations (2), makes it possible to theoretically establish qualitatively and quantitatively evaluate the values of the consumption of nutrients and elements, as well as quickly predict the course of the technological process [10,12,14,19].

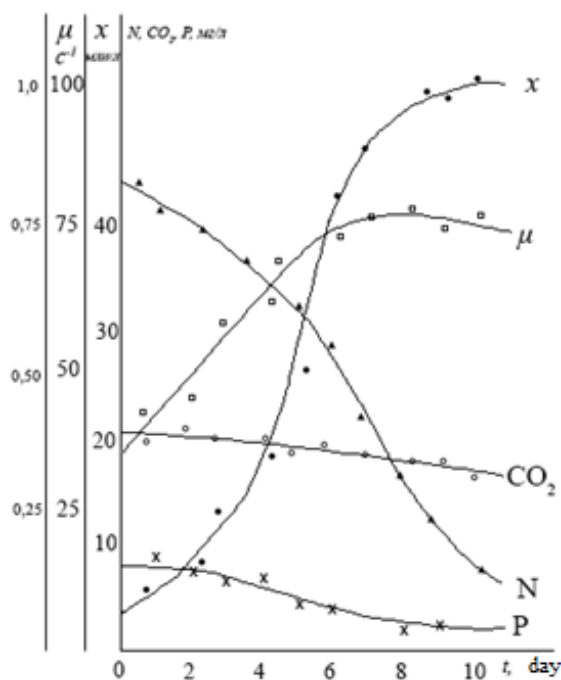


Figure 2. Dependence of the main indicators of chlorella cultivation on time in a batch mode of the process.

Shown in fig. 2. Comparative data allows you to establish the adequacy of the models obtained in the form of equations (1), describing periodic cultivation modes, to the real process.

Since the considered process of cultivating chlorella is carried out in a continuous mode, it is necessary to check the adequacy of the models obtained in the form (2).

The model of the chlorella cultivation process was solved by the Kutt-Merson method. The block diagram of the algorithm for solving the equations of the model is shown in Fig. 3. When solving the system of equations (1), the initial data were taken from experimental data obtained directly on the object under study, as well as from the results of laboratory analyzes.

During the simulation, the following initial conditions were taken:

$$X(t) = 20 \text{ mg/l}; \text{SN} = 45 \text{ mg/l}; \text{So} = 14 \text{ mg/l}; \text{SCO}_2 = 30 \text{ mg/l}.$$

At the same time, the restrictions imposed on the process were also taken into account. Technological parameters were maintained at $V = 1 \cdot 6 \text{ m}^3/\text{day}$ ($V = 1.4 \text{ m}^3/\text{day}$). The residence time of chlorella in the reactor was taken within 10 days $> t > 2$ days or ($240 \text{ h} > t > 46 \text{ h}$).

The cultivation time in continuous mode is in the range

$$T = \frac{V}{U} = (2 \div 10)$$

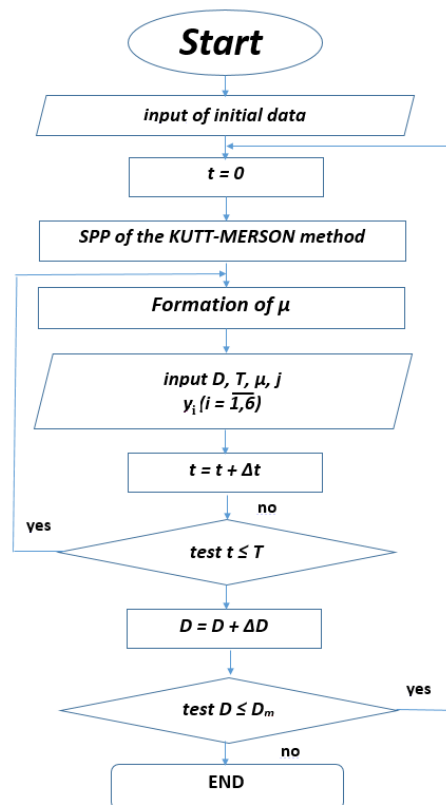


Figure 3. Block - scheme for calculating the main indicators of the cultivation of chlorella in a continuous mode of the process.

The reciprocal value of the residence time in biotechnological objects is the wort flow rate lying within the limits.

Based on the simulation results, the dependences of the change in the concentration of chlorella on time were obtained for various values of the flow rate (Fig. 3).

The process was studied at values of $0.21 \text{ m}^3/\text{h}$

$$240X > t > 0 \text{ and } 0.02r - 1 > 6 > 0$$

An analysis of the process modes based on the results of modeling showed that at $U_p = 4 \text{ m}^3/\text{day}$ (volumetric sampling rate), chlorella is washed out of the fermenter and does not have time to grow (Fig. 3). Reducing the rate of selection leads to a gradual increase in the volume of chlorella in the fermenter, which requires a certain amount of nutrients to support the life of excess chlorella.

On fig. Figure 3 shows curves that allow us to conclude that the growth rate of chlorella does not depend on the rate of circulating flow.

3. Research results

The results of the calculations carried out on the model described by equations (1) and (2) made it possible to quantify the costs of nutrients necessary for the growth and reproduction of microalgae, to establish the required rate of culture selection from the fermenter, to determine with the necessary accuracy the growth rate of a hundred microorganisms with taking into account the necessary group of factors that have a direct impact on the course of cultivation.

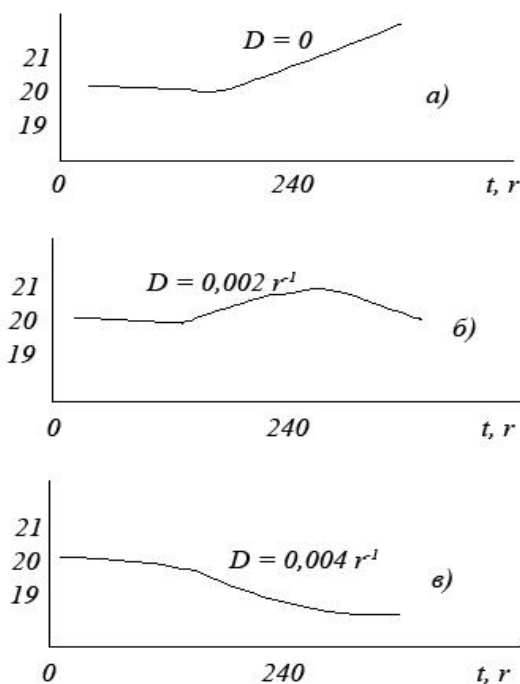


Figure 4. Dependences of changes in the concentration of chlorella from time to time at different values of the flow rate: a) $-D=0$; b) $-D = 0.0024-1$; c) $-D=0.0044-1$.

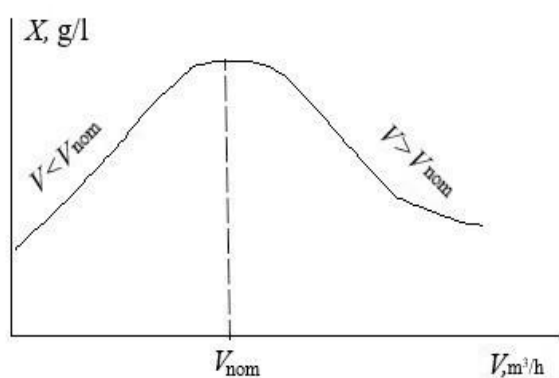


Figure 5. Change in the concentration of chlorella depending on the volumetric velocity V ; V_{nom} - nominal volumetric velocity

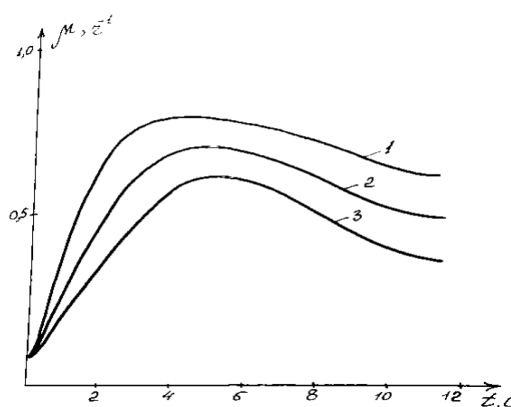


Figure 6. The dependence of the flow of change in the growth of chlorella on the speed of the circulating flow:

Thus, based on the analysis of the results of the simulation carried out on a computer, it becomes possible to determine the reliability of the theoretically derived equations describing the main

phenomena of the chlorella cultivation process, to quantify the technological parameters, to use the proposed model for the purposes of optimization and automatic control, and to practically solve various research and applied tasks.

In relation to the requests of the technological process of cultivating chlorella, it is necessary to evaluate the effectiveness of procedures for stabilizing the main parameters (composition of nutrients, physico-chemical and biological variables, as well as the quality and quantity of the output product). In this case, one has to solve a dilemma: whether to choose an expensive monitoring and control system, but providing the required sufficiently rigid stabilization of the process parameters, or to prefer a system of lower cost, but inferior to the first in accuracy.

A similar problem occurs when choosing means of control over technological parameters. In this case, it is necessary to find the most acceptable ratio between the accuracy and the cost of instrumentation. In addition, it is also necessary to keep in mind the issues of algorithmization, i.e. the automation process of all stages and procedures of mathematical modeling and related to analysis, synthesis, design, diagnostics and forecasting of the production process. All this requires the solution of a number of research problems related to the examination of the control object, the compilation of a mathematical description, the conduct of experimental studies to establish the coefficients and parameters of the model, the solution of optimization problems and the development of control and management algorithms, etc., complex of applied programs for solving modeling and control problems was developed, which, in turn, required significant costs.

Based on the above, it seems appropriate to evaluate the economic efficiency of the developed systems, control, forecasting and management of the quality and composition of technological environments and the optimal choice of technical means of control and management. The stabilization requirement is reduced to maintaining the parameters (the quality and content of the produced chlorella, and such of its biologically active state, which allows for the productive growth and reproduction of microorganisms within the specified limits) while observing environmental standards of production.

At the same time, the forecasting and control system should provide a reliable and prompt assessment of the suitability of the produced target product in terms of the content of protein, fat, etc. in the culture.

To build and implement control systems, the obtained mathematical models of kinetics (1) of the model of the hydrodynamic structure of flows in the cultivator (2) were preliminarily processed on a PC, methods for determining the parameters of the model, algorithms for predicting the course of the technological process and control were worked out.

Tests of the obtained models and control algorithms as part of control systems were initially carried out at a laboratory facility at the Institute of Microbiology of the Academy of Sciences of the Republic of Uzbekistan. Further, experimental confirmation of the effectiveness of the algorithms that are part of the software for the proposals of control systems was also obtained in production conditions.

The technical protocol of the proposed control systems is a set of technical means, consisting of specific instrumentation, local automatic regulation and control systems, a PC, as well as a communication device with the object [5].

The automatic regulation and control system timely monitors and stabilizes the control parameters at a given value, and also transmits information for the implementation of models and algorithms for predicting and controlling the course of the technological process.

The required duration of the experiments is set equal to one month. This conclusion was made based on the analysis of the features of a particular technological process, taking into account the requirements of the regulations, the operating experience of control systems, and also taking into account the time required to obtain a tangible technical and economic effect from the introduction of a control system. At the same time, the calculation of economic efficiency was carried out by taking into account the actual economic effect (increasing the yield of chlorella per unit of nutrients consumed, reducing the excessive consumption of nutrients for the growth and reproduction of chlorella, as well as for maintaining the vital activity of the culture, increasing the productivity of the cultivator, etc., achieved at individual stages of the implementation of control systems.

Consider the methodology for testing control systems for the technological process of cultivating chlorella.

The following systems were implemented to collect, store and process information about the state of the object.

- regulation of nutrient consumption
- regulation and control of medium temperature;
- pH regulation of the medium;
- level control;
- lighting control;
- control of nutrient content;
- control of the content of dissolved CO₂ in the medium.

The flow rate of nutrients is determined by the readings of the flow meters installed on the nutrient supply line, as well as by the level gauge.

When solving the problem of optimization and control, the values of chlorella concentration, growth rate, nutrient content and other indicators were taken according to the results of solving the systems of equations of the proposed model (2).

During the experiments, some parameter values were determined by laboratory analysis. At the same time, sampling was carried out every hour, including the time of sampling and laboratory analysis.

4. Findings

The implementation of control systems based on the developed mathematical models, optimization and control algorithms, as well as tested software systems made it possible to increase the yield of chlorella per unit of consumed nutrients, increase the productivity of the cultivator due to optimal maintenance of the flow rate, etc. .

The nature of the change in the main characteristics of the chlorella cultivation process (nutrient consumption G_i , chlorella X concentration, CO₂ content under manual control, with a local automatic control and monitoring system) that take place during the operation of control systems based on the proposed models and algorithms.

When modeling the process of cultivating microalgae, it is advisable to build an analytical model based on physicochemical, biological, hydrodynamic; mass transfer patterns, which is designed to contribute to a more accurate prediction of the process of growth and reproduction of microalgae and solving problems related to the design of new cultivators, optimization of existing processes and their automatic control.

The results of computer modeling made it possible to quantify the costs of nutrients necessary for the growth and reproduction of microalgae, to establish the required rate of culture selection from the cultivator, to determine the growth rate of microorganisms with the necessary accuracy, taking into account factors directly affecting the cultivation process.

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