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IMPROVEMENT OF THE METHODOLOGY FOR OPTIMIZING THE PARAMETERS OF COMPLEX SYSTEMS UNDER THE INFLUENCE OF THERMAL LOAD SOURCES

The article investigates some aspects of solving the problem of constructing mathematical models for optimizing the parameters of local laser action on multilayer microbiological systems. The constraints on the desired laser parameters and on the temperature field in the material subject to laser fission are set. Verification of compliance with the restrictions on not exceeding the maximum value of the temperature field requires multiple calculations of the corresponding temperature field in the microbiological material. Control over the temperature field limits ensures the viability of its parts during the biotechnological process of laser fission.

To construct adequate optimization mathematical models, the author substantiates the adequacy of the computational mathematical models describing the state of a microbiological system under the action of laser radiation sources. A multi-point boundary value problem with a system of inhomogeneous differential heat conduction equations for a multilayer microbiological medium is investigated and the correctness of this problem is substantiated for minor perturbations of the right-hand side of the differential equation. The results obtained in the article guarantee the adequacy of applied optimization mathematical models for finding rational values of technical parameters of laser emitters.

In order to improve the accuracy of optimization of the technical parameters of laser emitters, the article presents a mathematical modeling of the preparatory stage of embryo defrosting. The presented mathematical models and methods of their implementation are necessary to improve the quality of embryo defrosting. Improvement of the methodology for solving applied biotechnological problems will certainly lead to the complication of mathematical models, but it will increase the accuracy of calculation and optimization of technical parameters of the biotechnological process of laser embryo division.

Keywords: preparatory stage, mathematical models, correctness, applied tasks.

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ВДОСКОНАЛЕННЯ МЕТОДИКИ ОПТИМІЗАЦІЇ ПАРАМЕТРІВ СКЛАДНИХ СИСТЕМ ПІД ДІЄЮ ДЖЕРЕЛ ТЕРМІЧНОГО НАВАНТАЖЕННЯ

В статті досліджені деякі аспекти розв'язання задачі побудови математичних моделей для оптимізації параметрів локальної лазерної дії на багатошарові мікробіологічні системи. Задані обмеження на шукані параметри лазера і на температурне поле у матеріалі, що підлягає лазерному діленню. Перевірка виконання обмежень неперевищення максимального значення температурного поля за своє припустиме вимагає багаторазового розрахунку відповідного температурного поля у мікробіологічному матеріалі. Контроль за обмеженнями на температурне поле забезпечує життєздатність його частин під час біотехнологічного процесу лазерного ділення.

Для побудови адекватних оптимізаційних математичних моделей автором обґрунтована адекватність розрахункових математичних моделей, що описують стан мікробіологічної системи під дією джерел лазерного випромінювання. Досліджена багатоточкова крайова задача з системою неоднорідних диференціальних рівнянь теплопровідності для багатошарового мікробіологічного середовища і обґрунтована коректність цієї задачі за незначними збуреннями правої частини диференціального рівняння. Отримані в статті результати гарантують адекватність прикладних оптимізаційних математичних моделей пошуку раціональних значень технічних параметрів лазерних випромінювачів.

З метою підвищення точності оптимізації технічних параметрів лазерних випромінювачів у статті здійснене математичне моделювання підготовчого етапу розморожування ембріона. Наведені математичні моделі і методи їх реалізації потрібні для підвищення якості розморожування ембріона. Вдосконалення методики реалізації прикладних біотехнологічних задач безумовно ускладнить математичні моделі, однак це підвищить точність розрахунку і оптимізації технічних параметрів біотехнологічного процесу лазерного ділення ембріонів.

Ключові слова: підготовчий етап, математичні моделі, коректність, прикладні задачі.

Formulation of the problem

In order to reduce the consumption of expensive biomaterial in the biotechnological process of laser division of embryos, it is necessary to take into account the stage of preparation of embryos for the biotechnological process. Before the beginning of laser division embryos are stored frozen in liquid nitrogen, it is necessary to thaw embryos to avoid ruptures of cell membranes caused by jumps in thermal stress. Mathematical models and computational methods that are involved in the preparatory stage do not directly participate in mathematical modeling and optimization of biotechnological process parameters and simulate the stage of preparation of microbiological objects for biotechnological process. However, to guarantee the quality of the biotechnological process, the importance of the stage of preparation of the embryo for manipulation cannot be underestimated.

The computational mathematical model that describes the state of the embryo under laser influence is a nonlocal boundary value problem of the system of evolutionary differential equations of heat conduction. Using methods from the theory of pseudodifferential operators over the space of generalized functions of slow step growth, the author proved the correctness of the above boundary value problem. Taking into account the structure of the embryo under laser water action and specific features of boundary value problems has a decisive influence on the choice of methods for calculating temperature fields. In this case, the author used the Fourier methods of separated variables and uncertain coefficients to solve the boundary value problems. Despite the fact that the calculation and optimization of technical parameters at the preparatory stage will increase the complexity of mathematical calculations, this, at the same time, will increase the accuracy of the solution of applied problems of optimization of the biotechnological process of laser division of embryos.

Analysis of the latest research

In articles [1–3] mathematical models of cell membrane electroporation are developed, and methods for optimizing energy consumption in solving certain applied biotechnological problems are given. Using methods of nonlinear approximation, the authors of [3] summarize the dependence of conductivity values on the values of pulsed electric field strength. In [4] a review of existing techniques of cell membrane dissection for the purpose of germ separation was carried out, the disadvantages and advantages of laser impact on the membrane for cell division were analyzed. Thus, despite taking into account the multilayer structure of the embryo, the calculation of the laser exposure temperature in the article [4] does not take into account the different thermophysical parameters of the embryo layers, which increases the error of the calculated excess exposure temperature and, as a result, increases the thermal traumatization of embryos during laser division. In publications [5, 6], mathematical models have been developed for some technical systems with distributed parameters containing sources of thermal effects. The authors of the paper [6] focused on the issues of determining and substantiating the conditions of correctness of boundary value problems that describe the state of the modeled systems. In [7–9], a number of mathematical models and computational methods of their implementation for optimizing the parameters of specific technical systems are given. Of particular note are the publications [8, 9], which contain methods and algorithms for solving applied problems of geometric design and include methods for optimal placement of objects of complex geometric shape in a given pre-fixed area. The articles [10–12] show the use of mathematical tools for solving applied cybersecurity problems.

The purpose of the work is improve the methodology of mathematical modeling and optimization of biotechnological systems by taking into account the step of embrion thawing before laser fission.

Presenting main material

The above mathematical model is an auxiliary model and is not related to the optimization of the vector of laser exposure parameters. However, it is important from the point of view of qualitative fulfillment of the whole biotechnological process of laser division of microbiological material. When investigating these issues, it is worth noting the publication [13], which contains mathematical models and methods for determining the quality of seed material before the implementation of technological processes. Microbiological material is usually stored frozen in liquid nitrogen. Before performing its division, the material must be thawed without tissue rupture. This means that during embryo thawing, appropriate parameters must be controlled to guarantee acceptable thermal stress values. The uniformity of the final temperature field distribution in the microbiomaterial volume Ω can be characterized by the following mathematical model:

$$\left(\max_{\substack{(x,y,z)\in\Omega^* \\ t\in\left[t_0;t^*\right]}} T(x,y,z,t) - \min_{\substack{(x,y,z)\in\Omega^* \\ t\in\left[t_0;t^*\right]}} T(x,y,z,t) \right) \to \min_{z^*\in Z}, \quad (1)$$

where $T(x,y,z,t)$ – temperature field of the point area $(x,y,z)\in\Omega^*$ of multilayer microbiologic material Ω;

t_0, t^* – initial and final moments of time heat exposure.

In this case, it is necessary to fulfill the restriction on the minimum and maximum values of the temperature field in the microbiomaterial Ω:

$$\begin{cases} T_1^* \le \max T \le T_2^*; \\ T_3^* \le \min T \le T_4^*, \end{cases} \quad (2)$$

where T_1^* – the specified minimum permissible value of the maximum temperature field;

T_2^* – the specified maximum permissible value of the maximum temperature field;

T_3^* – the specified minimum permissible value of the temperature field minimum;

T_4^* – the specified maximum permissible value of the temperature field minimum.

For correct formulation of the boundary value problem describing the temperature field of a multilayer biomaterial, it is necessary to set initial conditions in the form of the temperature field distribution at the initial moment of time, after defrosting:

$$T(x,y,z,t)\big|_{t=t_0} = T^{**}(x,y,z), \quad (3)$$

where T^{**} – temperature field distribution in the area of multilayer microbiological material after the end of the thawing process and before the laser fission.

Regarding the formulation of the control problem of the biotechnological process of biomaterial defrosting, it should be noted that for this purpose it is necessary to carry out the parameterization of the biomaterial temperature field by representing the corresponding temperature field depending on the control parameters. In this case, in the mathematical model (1) the temperature field is represented as:

$$T = T\left(x, y, z, t, Y\right), \quad (4)$$

where Y – vector of defrosting process control parameters, the components of which are subject to appropriate constraints inherent in the technological means providing the defrosting process.

To control thermal stresses caused by jumps in the values of the temperature field gradient vector, it is necessary to minimize the maximum value of the modulus of the temperature field gradient in the area of points of the multilayer microbiological material Ω, find:

$$\min_{z^* \in Z} \left[\max_{\substack{(x,y,z)\in\Omega^* \\ t\in[t_0;t^*]}} \left| grad\, T\left(x, y, z, t, z^*\right) \right| \right]. \quad (5)$$

To substantiate the correctness of the above applied optimization mathematical models it is possible to apply mathematical methods given in the articles of the author [14, 15]. Their essence is that the correctness of boundary value problems describing the thermophysical system «embryo under laser influence» determines the correctness of applied optimization mathematical models. To prove the correctness of boundary value problems the symbol of the differential equation is divided into the sum of several symbols and for them it is proved that the conditions of subordinated symbols to the differential operator and exponentially correct polynomials of constant power in spaces of generalized functions of slow step growth bounded on the segment of the real axis are fulfilled. Besides, to increase the accuracy of optimization of the selected technical parameters of laser emitters it is necessary to implement not one but as many applied optimization mathematical models as possible. The number of iterations depends on the total time allotted for parameter optimization and on the optimization accuracy initially set.

Conclusions

The article proposes an applied optimization mathematical model, which is used to improve the accuracy of unfreezing ofembryos before laser fission. At this stage, to avoid rupture of cell membranes it is necessary to stabilize the behavior of the temperature field gradient vector caused by jumps in thermal stress. The author noted that the peculiarity of the object of study is that its state is described by a boundary value problem for a system of partial differential equations (a system with distributed parameters). This specificity considerably complicates both the process of constructing appropriate mathematical models for optimizing the parameters of laser radiation action on multilayer microbiological materials and their use to improve the quality of the biotechnological process of biomaterial fission. For justification of correctness of boundary value problems the author used specialized methods and estimates on the functions of solutions in the space of generalized functions of slow step growth. Application of the research results of this article for solving many applied optimization problems will make it possible to increase the accuracy of control of technical parameters, which guarantees acceptable values of thermal stresses, and reduce the traumatizability of embryos during laser fission.

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