Methods of Mathematical Programming for Designing a Safe Environment for Bioobject

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Abstract

To determine the necessary conditions for creating a safe environment for the embryo exposed to a laser beam and increasing cell viability, we researched to calculate the optimal technical parameters and temperature indicators of laser exposure to the embryo. For this purpose, we controlled the temperature conditions of laser action on the embryo. The calculated mathematical model of laser action is presented, and the temperatures of laser action on the layers of the embryo are calculated by using the methods of separated variables and uncertain coefficients. Using the surface-volume ratio of the volume of thermally injured cells to the volume of the embryo cell layer, an applied optimization mathematical model for minimizing the volume of thermally injured embryos was implemented. This made it possible to calculate the optimal power and time of laser exposure to the embryo. Thus, the application of the results of this study made it possible to determine the parameters of the safety environment for a bioobject (embryo) in which the latter is unevenly heated. The results of the above studies can be used in solving general problems aimed at improving the quality of functioning of several technical systems with distributed parameters containing concentrated, discrete sources of scanned laser radiation.

Keywords

Environment, information security, bioobject, computational mathematical model, optimal parameters.

1. Introduction

From the point of view of innovative biotechnology projects, the security environment is a set of external and internal relations related to certain biotechnological manipulations with a bioobject, as well as conditions, factors, and circumstances that have influenced and may influence these relations in a certain way. The stimulators of the development of the security environment are known to be the interests of forces, and all actions of such forces are aimed at achieving their own or group interests. In the context of our study, the interests of the forces mean, on the one hand, the interests of the project implementers, and on the other hand, the interests of competitors. It is the competitors who are interested in causing damage, liquidation of the project, or destruction of its main objects at the first stages of implementation of an innovation project, and in discrediting the results among the scientific or business community at later stages. Therefore, understanding the true interests of competitors is a priority task in predicting and implementing the conditions of the project's security environment [1–2]. The interests of the forces are manifested and specified in the problems of relations that arise during interaction and are hidden. According to innovative projects, the interests are aimed at obtaining/preserving information that constitutes scientific and commercial secrets and provides advantages in the competitive struggle. Therefore, understanding the true

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interests of the actors is a priority task for creating conditions for project information security.

For this study, we have chosen an innovative project that is intended to be implemented in the activities of a biotechnology laboratory, institute, veterinary medicine center, etc. [3–4]. Its essence is to calculate the optimal parameters and improve the quality of the safe environment where the embryo is exposed to a laser beam. The purpose of our study is to apply mathematical programming methods to determine the optimal conditions of the safe environment for the embryo. Given that a bioobject is a living organism, such conditions can be considered a safe environment for it, because in this environment it remains safe and can maintain its own life, develop, and reproduce.

An increase in the quality of laser division of the embryo is achieved by creating conditions of a pectic-free medium where the embryo is placed, by increasing its viability in the biotechnological process. It is necessary to provide control over the temperature conditions of laser heating and the consumption of technical resources (power and time) of laser emitters. Control over temperature regimes can be ensured through the implementation of restrictions not to exceed the temperature of heating of the embryo for 37^0C during multiple iterative processes of realization of computational mathematical models (boundary value problems) for multidimensional, non-stationary differential equations that describe the state of the embryo under laser influence. Due to the specificity of boundary value problems and specific features of the temperature function of the embryo, it is impossible to guarantee the existence and uniqueness of their solutions (multidimensionality, nonlinearity). To justify the correctness of mathematical models, the authors propose to use specialized methods and estimates from above on the solving functions of solutions of differential equations in the space of smoothly growing distributions of slow degree growth. This will allow us to obtain necessary and sufficient conditions for guaranteeing the correctness not only of the above mathematical model but also of applied optimization mathematical models of the process of laser treatment of the embryo, as well as of the general problem of creating an ash-free environment for the bioobject by increasing the viability of the separable parts of the embryo.

2. Literature Review

In [5–6], computational mathematical models were developed for thermophysical and mechanical systems containing sources of physical field loading. Necessary and sufficient conditions for the stability of solutions for systems of nonlinear differential equations with a small external perturbation in the right-hand side of the main differential equation of the boundary value problem were determined and proved [7–8]. The authors of [9] solve the problem of determining the correctness conditions for boundary value problems with systems of linear, inhomogeneous partial differential equations. The authors derive hyperbolicity conditions for solutions of homogeneous and inhomogeneous impulse systems with distributed parameters. Paper [10] solved some partial problems of optimizing the parameters of technical, mechanical, and thermophysical systems containing local, concentrated load sources.

Methods for improving the accuracy of solving applied problems of cutting a fixed-size area [11] into smaller parts to reduce waste of the material to be cut are presented. Using well-known methods and mechanisms of linear mathematical modeling, the authors of [12] approximated nonlinear control systems, which allows to increase the accuracy of calculations using numerical methods of approximate values of the function of solutions of boundary value problems on a computer. It should be noted that the mentioned publications were not related to the use of laser radiation on microbiological objects.

Our publication is in the context of previous scientific research, which the authors were engaged in in different years to increase the effectiveness of the implementation of innovative developments in various branches of agriculture and agrarian business, in particular [13–14]. In publications [15–16], mathematical models and methods for animal husbandry are proposed, namely, for the development of hardware (software and hardware) means of diagnosing the quality of cow’s milk and improving the quality of the lactation process.

In the articles [17–18], applied optimization mathematical models were developed and numerical methods for the selection of rational trajectories (division trajectories) of the embryo were improved, taking into account the specifics of the modeled systems. The use of the results obtained by the authors of the works in practice allows for an increase in the accuracy and speed of the implementation of applied biotechnological tasks for the optimization of the parameters of multilayer objects.

Some aspects of solving applied optimization problems to improve the design quality of biotechnological systems in agriculture are studied in publications [17–19]. Thus, the authors of the article [17] solved the problem of minimizing trauma to embryos by optimizing the technical parameters of laser emitters and choosing the optimal trajectory of laser division of embryos, developed applied optimization mathematical models, and proposed methods of their implementation to optimize the parameters of the biotechnological system “embryo under laser exposure.” The application of the obtained results, published in [18–19], in practice, allows for an increase in the accuracy and speed of designing systems with distributed parameters.

However, the parameters of the safety environment for such biological objects, which are under laser radiation and allow them to be viable, have not been determined. Therefore, this publication is relevant and allows you to solve exactly these questions.

3. Problem Formulation

Determine the parameters of the safety environment where the embryo is located, which should be created for a specific bioobject.

4. Methods

To calculate the temperature regimes of laser heating of the embryo, it is necessary to solve the computational mathematical model (boundary value problem) of the process of laser action on the embryo. Boundary value problem of the system of differential equations of heat conduction describing the state of an embryo under laser influence:

$$\begin{cases} 5.46\frac{\partial T_1}{\partial t} = 0.71\left(\frac{\partial^2 T_1}{\partial r^2} + \frac{2}{r_1}\frac{\partial T_1}{\partial r}\right) + 55.02; \\ 5.44\frac{\partial T_2}{\partial t} = 0.96\left(\frac{\partial^2 T_2}{\partial r^2} + \frac{2}{r_2}\frac{\partial T_2}{\partial r}\right) + 94.1; \\ 5.3\frac{\partial T_3}{\partial t} = 0.94\left(\frac{\partial^2 T_3}{\partial r^2} + \frac{2}{r_3}\frac{\partial T_3}{\partial r}\right) + 390.25; \\ 5.1\frac{\partial T_4}{\partial t} = 0.91\left(\frac{\partial^2 T_4}{\partial r^2} + \frac{2}{r_4}\frac{\partial T_4}{\partial r}\right) + 452.4. \end{cases} \quad (1)$$

The Dirichlet boundary conditions at the beginning and the end of laser heating:

$$\left[\begin{array}{l} T(0;0) = 100\ ^0C; \\ T(53;2550) = 37\ ^0C. \end{array}\right. \quad (2)$$

Boundary conditions of the 3rd kind, specifying the specific heat flux from the embryo to the environment where this microbiological object is placed:

$$-0,67\frac{\partial T_1}{\partial r}(0,t) = 4,4. \quad (3)$$

Using the methods of separated variables and indeterminate coefficients, we obtained the solution of the differential equation (1), which we will write based on the general form of the boundary value problem (1)-(3):

$$\begin{cases} c_1 e^{ct_1}\left(1 + \frac{cr_1^2}{9a} + \ldots\right) = T(r_1, t_1) + \frac{qr_1^2}{6a}; \\ c_1 e^{ct_2}\left(1 + \frac{cr_2^2}{9a} + \ldots\right) = T(r_2, t_2) + \frac{qr_2^2}{6a}, \end{cases} \quad (4)$$

where $T(r,t)$ is laser exposure temperature; q is the power density of heat loads in the layers of the embryo; a is diffusivity coefficient.

We divide the first equation by the second equation to find the unknown constants:

$$e^{c(t_1 - t_2)} = \left(\frac{T(r_1,t_1) + \frac{qr_1^2}{6a}}{T(r_2,t_2) + \frac{qr_2^2}{6a}}\right) \times \left(\frac{1 + \frac{cr_2^2}{9a}}{1 + \frac{cr_1^2}{9a}}\right). \quad (5)$$

Let's find the constant c_1:

$$c_1 = \frac{T(r_1,t_1) + \frac{qr_1^2}{6a}}{e^{ct_1}\left(1 + \frac{cr_1^2}{9a}\right)}. \quad (6)$$

We got it:

$$e^{-1097c} \approx \left(\frac{63530}{147660}\right) \times \left(\frac{1 + 1045,7c}{1 + 769,2c}\right),$$

$$\left(\frac{63530}{147660}\right) \times \left(\frac{1 + 1045,7c}{1 + 769,2c}\right) = 1,$$

and therefore $c_1 \approx 264708,3$.

Thus, the temperature of heating of the

perivitelline space:

$$T_2(r,t) \approx 88{,}7\ ^0C.$$

Having made similar calculations, we obtained the heating temperature of blastomere cells $T_3(r,t) \approx 63\ ^0C$.

The temperature that is required to maintain the viability of the blastomere cell layer is 37⁰C. When exposed to a laser beam on an embryo with a temperature greater than the 37⁰C the microbiological object is injured. To calculate the volume V_{sc} of a heat-injured segment of embryonic embryos, it is possible to use the following formula:

$$V_{sc}(T) = \pi\left(r_1 h_1^2 - \frac{h_1^3}{3}\right) + \pi\left(R h_2^2 - \frac{h_2^3}{3}\right) \qquad (7)$$

where r_1 is depth of laser beam penetration into the blastomere cell layer; $h_1 = C_1B$, $h_2 = C_2B$ is segments of the segment connecting the geometric center of the embryo and the laser beam source of action in the form of a spot; R is radius of the cell layer.

Note that the volume $V_{zp+pp}(T)$ segment of the layers of the pellucid zone and perivitellar space of the embryo is calculated by the formula (7). In this case $r_1 = O_1A$ – is the depth of penetration of the laser beam into the perivitellated space.

To find the values h_1, h_2 from the formula (7) consider a triangle O_1O_2A, formed by the segments r_1, R and the segment connecting the geometric center of the blastomere cell layer and the laser beam source of action in the form of a spot (Fig. 1).

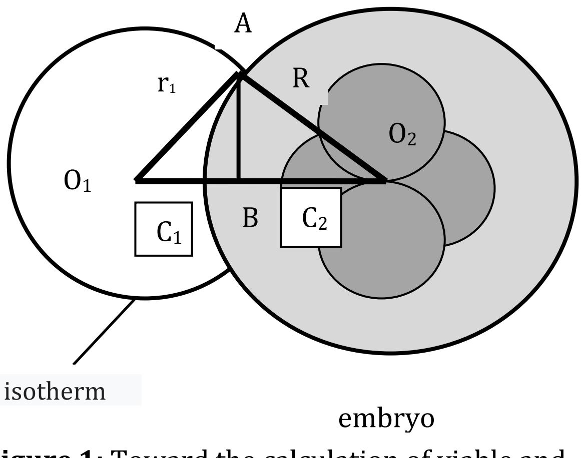

Figure 1: Toward the calculation of viable and thermally injured portions of the blastomere cell layer

Using Heron's formula, we find the area of the triangle O_1O_2A, and then divide the found area by the length of the side O_1O_2. Thus, the formula for determining the length of the height AB has the following form:

$$AB = \frac{2\sqrt{p(p-r_1)(p-R)(p-O_1O_2)}}{O_1O_2},$$

where $p = \frac{O_1A + O_2A + O_1O_2}{2}$ is half-perimeter.

To find the segments h_1, h_2 parties O_1O_2 calculate the length of the segments O_1B, O_2B:

$$\begin{cases} O_1B = \sqrt{r_1^2 - AB^2}; \\ O_2B = \sqrt{R^2 - AB^2}. \end{cases} \qquad (8)$$

Knowing the length of the segments O_1B, O_2B, calculate the lengths of the segments we are looking for $h_1 = C_1B$, $h_2 = C_2B$:

$$\begin{cases} h_1 = C_1B = r_1 - O_1B; \\ h_2 = C_2B = R - O_2B. \end{cases} \qquad (9)$$

Substituting the found values h_1, h_2 in formula (7), let us calculate the volume of the thermally traumatized segment of the embryo blastomere cell layer, taking into account the volume of $V_{zp+pp}(T)$ a segment of the irradiated layers of the pellucid zone and perivitellar space.

To determine the volume $V_{sc}(T)$ of the heat-traumatized segment of the embryo blastomere cell layer, it is necessary to subtract the volume of the irradiated segment of the embryo blastomere cell layers, perivitellar space, and pellucid zone from the volume of the segment of the irradiated embryo blastomere cell layers, perivitellar space and the pellucid zone $V_{zp+pp}(T)$ segment of the irradiated layers of the pellucid zone and perivitellar space of the embryo.

To find the volume of the blastomere cell layer, it is possible to use the following expression:

$$\frac{V}{V_c} \approx \frac{n}{2}, \qquad (10)$$

where V is the volume of the blastomere cell layer; V_c is the volume of one cell; n is cell count.

Using the data on the radius and number of blastomere cells characteristic of the embryo at the late morula stage of development, we obtained that the volume of the blastomere layer is equal to $138430,7\pi$ the micrometer. To calculate the optimal values of power and time of laser exposure, it is necessary to implement an applied optimization mathematical model of minimizing the volume of thermally injured cells at the selected parameters of laser exposure [20–23]:

$$K = \frac{V_{etc}}{V_c} \to \min, \qquad (11)$$

where V_{etc} is the volume of the thermally traumatized segment of the cell layer, which is calculated by the formula (7).

Thus, applying the surface-volume relation from the above-applied optimization mathematical model, for a countable finite number of iterations from the solution of boundary value problems (1)–(3), we obtained the optimal parameters of the safe environment (power in the 124 milliwatts and the duration of laser exposure in 3 microseconds).

5. Conclusion

The article proposes mathematical models and methods of their realization to control the temperature modes of laser heating of embryo, to search for optimal parameters of laser exposure on embryo. An applied optimization mathematical model for minimizing the volume of thermally-injured blastomere cells is proposed. It is based on the surface-volume ratio of the volumes of traumatized cells of embryos to the volume of the whole cell layer. Having applied specialized methods from the theory of nonlinear mathematical programming in the space of generalized functions of slow step growth, the correctness of the given computational and applied optimization mathematical model is proved.

The results of the researches carried out in this work are expediently applied to increase the viability of microbiological objects under the influence of physical field sources by improving the quality of the safe environment where they are placed.

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