Non-contact heat transfer models identification: Laser hyperthermia of superficial human tissues

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Abstract. Planning and predicting the processes of biological tissues heating associated with therapeutic effects involves high-precision mathematical modelling. However, the thermophysical properties of tissues can vary greatly from patient to patient. The paper presents a computational and experimental method for identifying mathematical models of heat transfer, not involving the placement of temperature sensors inside of the studied object. The experimental setup consists of a flat sample of the material, a laser setup, and a thermal imaging camera. The surface thermal response to the pulsed heat flux of the laser is an array of input data for the developed software package. The heat transfer coefficient and heat flux density are determined iteratively by minimizing the residual functional between the calculated and experimental values. The method was tested when determining the characteristics of a specimen of low-pressure polyethylene. The result was obtained in 5 iterations and under the influence of external natural convection, and without taking into account the translucency of the material, a discrepancy of calculated and experimental values of 3.5% was shown. The method can be used to plan the therapeutic process in order to ensure its maximum effectiveness.

1. Introduction

Laser hyperthermia of superficial tissues (pulsed heating up to 41–45 °C) is a therapeutic method used in oncology [1]. To prevent the risk to the patient’s health, as well as to achieve the desired therapeutic effect, it is necessary to ensure a change in the temperature field of the tissue within the limits specified by the requirements of the method. Prediction and regulation of these processes require mathematical modelling, which is impossible without an accurate assessment of the thermophysical and radiation-optical characteristics of the tissue [2,3].

The determining of the model coefficients in this formulation is the inverse heat transfer problem. The solving of such problems traditionally involves measuring the temperature response of an object to external heat exposure. However, in the case of biological tissues, installing temperature sensors at a certain depth is undesirable. The only possible way to obtain information about the state of the system is to measure the surface temperature. Experience in solving inverse problems has shown that the most effective and universal approach is the use of extreme methods based on minimizing objective functionals [4].

The aim of this work was to develop a computational-experimental method for identifying a mathematical model of heat transfer of the superficial tissues under laser hyperthermia.
2. Materials and methods

2.1. Mathematical model

Mathematical modelling of heat transfer was based on the description of the method of laser hyperthermia of superficial tumours. Heat transfer provided by blood, in this case, can be neglected due to insignificant flow, and heat transfer is considered conductive [5].

A one-dimensional model is considered: an infinite plate with a thickness $d$ is heated by periodically turned on laser on the left border. Non-contact temperature measurement is performed at the point of heating.

The mathematical model of the proposed system is a classical heat transfer equation with boundary conditions and has the following form:

$$
C \frac{\partial T}{\partial \tau} = \lambda \frac{\partial^2 T}{\partial x^2}, \quad 0 < x < d, \quad 0 \leq \tau \leq \tau_{\text{max}}
$$

$$
T(x_0) = T_0
$$

$$
-\lambda \frac{\partial T}{\partial x}(0, \tau) = q_1(\tau) + \alpha(T(0, \tau) - T_0(\tau))
$$

$$
-\lambda \frac{\partial T}{\partial x}(d, \tau) = q_2(\tau)
$$

where $C$ is the heat capacity, $\lambda$ is thermal conductivity coefficient, $T$ is temperature, $d$ is the thickness of the sample, $\tau$ is time, $\alpha$ is the heat transfer coefficient, $q_1$ – laser heat flux on the left border and $q_2$ is heat flux on the right border of sample.

2.2. Identification Problem Solution

The solution to the problem of heat transfer mathematical model identifying is determining the set of system characteristics $\bar{u} = \{\alpha, q_{\text{max}}\}$ which could be formulated as a solution to the equation (2):

$$
A\bar{u} = f(\tau),
$$

and is based on minimizing the residual functional of the calculated and experimentally measured temperatures (3) by the iteration procedure.

$$
J(\bar{u}) = \int_{0}^{\tau_m} (A_m\bar{u} - f_m)^2 d\tau \leq \delta^2,
$$

The calculation algorithm is following. At the first stage, an initial approximation of the desired characteristics is set, based on a priori information or zero; then a direct boundary-value problem and a system of problems for increasing the temperature are solved. An array of irradiated surface temperature values was used as input data for the developed software package that implements the identification method of the mathematical model.

After that the initial values for solving the identification problem (determining the characteristics of the material by the response to external influences) should be chosen. Further, using the iterative regularization method, we determine such values of the desired characteristics for which the discrepancy between the experimental and calculated values (residual functional $J$ (3)) is minimal. At each iteration, the exit condition for calculations is checked.

The effectiveness of the proposed algorithm and the possibility of applying the residual criterion to exit the iterative process is shown in [6] for solving the problem of determining the characteristics of heat-protective materials.
2.3. Experimental setup

The application of the proposed identification technique involves an experimental study. For this, the following experimental scheme was developed.

A slab with sizes $3 \times 30 \times 30$ mm was fixed in such a way that the heat flux of the laser system with an infrared emitter with an output power of 3 W normally fell on one of its borders (the system corresponds to the energy levels used in laser hyperthermia). The thickness of the sample, at the same time, provides sufficient (at least 0.5 °C) for control measurements of the minimum temperature difference between the two surfaces. The experimental design is shown in Fig. 1.

![Diagram of experimental setup](image)

**Figure 1.** The scheme of the experiment. The low-pressure polyethylene plate 1 is heated by the heat flux of the laser system 2. Plate surface temperature is measured using a thermal imaging camera 3. 4 and 5 - control thermocouples.

For testing, a specimen of low-pressure polyethylene was made. The choice of material was due to its thermophysical characteristics comparable to those of the skin. Initial values of characteristics were: $\alpha = 0.1$ W/m²K, $q_{\text{max}} = 465$ W/m².

Correspondence of the temperature field in the plate to the real process was achieved by preheating the left boundary so that by the time the recording begins, the temperature of the right boundary was equal to body temperature (36.6 °C).

The temperature of the heated surface was measured using a thermal imaging camera. In addition, to control the course of the experiment, thermocouple sensors were located on the left and right surfaces of the plate. The readings of these sensors were not taken into account in the calculation.

A preliminary computational experiment made it possible to select a laser operating mode that provides the required temperature regime (40–42 °C) [7].

3. Results

As a result, the values of the heat transfer coefficient $\alpha = 3$ W/m²K and the amplitudes of the laser heat flux $q_{\text{max}} = 530$ W/m² for 5 iterations were restored.

The obtained values were used to solve the direct heat transfer problem. The discrepancy between the calculated values and the experimental data was 3.5 % (Fig. 2).
Figure 2. Comparison of calculated temperature values ($T_1$ - on the left and $T_2$ - on the right border) with experimental data ($T_{ir}$ - thermal imager readings). The laser mode $q_l$ is provided for reference.

4. Discussion
In this work we developed a computational-experimental complex method that provides a solution to the problem of thermal processes planning. An analysis of the features of heat transfer in biological tissues showed the need to revise the adopted approach to experimental testing involving contact temperature measurements at a certain depth of the sample [6]. Therefore, the experimental method presented above allows one to evaluate the applicability of the identification algorithm for mathematical models of radiation-conductive heat transfer. The resulting discrepancy between the calculated and determined during the experiment temperature values (Fig. 2) can be explained by the lack of consideration for the translucency of the material in the selected model, as well as by the probable effect of natural air convection and other possible methodological errors. Despite this, the solution to the problem of determining the complex characteristics of the system was completed in just 5 iterations.

The method of experimental development of methods for identifying heat transfer models proposed in the work allows us to implement a highly accurate mathematical description of hyperthermia processes and can be used to solve problems of ensuring safety and increasing efficiency when planning local and general heating of biological tissues as well as in cases where tissue heating is not the target process.

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