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BIOLOGICAL TISSUE DESTRUCTION UNDER LASER IRRADIATION

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Physical processes proceeding in a biological tissue under laser irradiation are described. Based on evaluation of all heat-mass transfer processes, a model of biological tissue destruction is proposed as the multiboundary-value Stefan problem with stepwise variation of thermophysical parameters at phase boundaries. To check the model adequacy, a one-dimensional problem has been numerically solved which makes it possible to determine the dimensions of carbonization zones and the boundary velocities. Analysis of the results obtained allows a conclusion to be made about the model adequacy to real processes of biological tissue destruction.

The problem of laser radiation-substance interaction goes back to the time when lasers of sufficient power were designed. Many experimental and theoretical works were carried out to investigate the interaction of radiation with homogeneous materials (metals). The processes of sublimation, photoablation, and photodestruction were studied. Destruction of a material with a complex chemical composition and an inhomogeneous structure may proceed in several steps and be accompanied by processes of chemical pyrolysis, giving rise to several phase boundaries [5, 6]. As for the interaction between high-energy radiation and an organic tissue, it combines the all possible destruction mechanisms [7, 8] and physical processes occurring with inorganic materials [9]. By virtue of this, mathematical consideration of these problems is impossible without preliminary development of a physical model of the process with certain assumptions.

Now we analyze the physical processes in the case when an organic tissue of epidermis is exposed to laser radiation with 200-mJ energy and pulse duration of 200 μsec. According to the investigation [7], the corresponding power density $4 \cdot 10^4$ W/cm^2 of focused radiation on the tissue causes its evaporation. Unlike photodestruction and photoablation, the evaporation processes are of a prolonged character (10^{-3}-1 sec), which allows definite conclusions to be drawn about stable phase boundaries upon destruction, and, therefore, mathematical formulation of the problem is reduced to the multiboundary-value Stefan-type problem. Next considering the destruction process, it is necessary to choose a model of the tissue structure. Let the epidermis be a composite material with interpenetrating components of carbon (10%) and water (90%), with the mean radius r of pores filled with water being smaller than the wavelength of incident radiation. This model is, naturally, abstract but it allows one to gain insight into the majority of such physical processes of destruction as evaporation of the aqueous component of the tissue, efflux of formed gases over the carbon skeleton, and destruction of the latter. These processes result in formation of two phase boundaries: epidermis-carbon skeleton and carbon skeleton-ambient air. A value of the pore radius less than the wavelength provides simplification of the boundary conditions. In this case the radiation does not penetrate inside the body and is fully absorbed on the surface (owing to the emissivity factor of the carbonized layer of the tissue being close to unity). Mathematically, the heat conduction equations corresponding to the given model are as follows:

$$c_1\rho_1 \frac{\partial T}{\partial \tau} = \lambda_1 \frac{\partial^2 T}{\partial x^2}, \quad \zeta_1 < x < \zeta_2; \tag{1}$$

$$c_2\rho_2 \frac{\partial T}{\partial \tau} = \lambda_2 \frac{\partial^2 T}{\partial x^2}, \quad x > \zeta_2. \tag{2}$$

Heat capacities per unit volume $c_1\rho_1$, $c_2\rho_2$ and thermal conductivities λ_1, λ_2 are calculated proceeding from the tissue structure in the following manner

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$$c_1\rho_1 = c_C\rho_C(1-\Pi),\quad c_2\rho_2 = c_{H_2O}\rho_{H_2O}\Pi + c_C\rho_C(1-\Pi),$$

$$\lambda_1 = \lambda_C[c^2 + \nu(1-c)^2 + 2\nu c(1-c)(\nu c + 1 - c)^{-1}],\quad \nu = \frac{\lambda_{air}}{\lambda_C},$$

$$\lambda_2 = \lambda_C[c^2 + \nu(1-c)^2 + 2\nu c(1-c)(\nu c + 1 - c)^{-1}],\quad \nu = \frac{\lambda_{H_2O}}{\lambda_C}.$$

Here c is a parameter characterizing the porous structure.

Conditions at the boundaries ζ_1, ζ_2 are of a form typical for the Stefan problems:

$$-\lambda_1 \left.\frac{\partial T}{\partial x}\right|_{x=\zeta_1} = q - \rho_C L_1(1-\Pi)\frac{d\zeta_1}{d\tau}; \tag{3}$$

$$-\lambda_1 \left.\frac{\partial T}{\partial x}\right|_{x=\zeta_2^-} + \lambda_2 \left.\frac{\partial T}{\partial x}\right|_{x=\zeta_2^+} = \Pi\rho_{H_2O}L_2\frac{d\zeta_2}{d\tau}. \tag{4}$$

To close the equations, it is necessary to have two more relations. In the Stefan problem (the liquid-solid boundary) it would be the equality of temperatures of both phases. However, in the given case sublimation proceeds (the gas-solid boundary) and for it in [1] an equation for the front velocity as a function of temperature is proposed:

$$\frac{d\zeta_1}{d\tau} = a\exp\left(-\frac{L_1A_1}{RT_1}\right). \tag{5}$$

For the boundary ζ_2, the front velocity of evaporation out of the porous structure will depend on the depth of the evaporation zone $\delta = |\zeta_2 - \zeta_1|$ (for a free-molecular flow pattern) [10]:

$$\frac{d\zeta_2}{d\tau} = \frac{a\exp\left(-\frac{L_2A_2}{RT_2}\right)}{1+\frac{\delta}{2r}}. \tag{6}$$

Thus, equations (1), (2) with boundary conditions (3) through (6) represent a closed mathematical statement of the Stefan problem with two moving boundaries. Now we pass to a moving coordinate system related with ζ_1:

$$\bar{x} = x - v\tau,\quad v = \frac{d\zeta_1}{d\tau}.$$

Then the equations will acquire the form

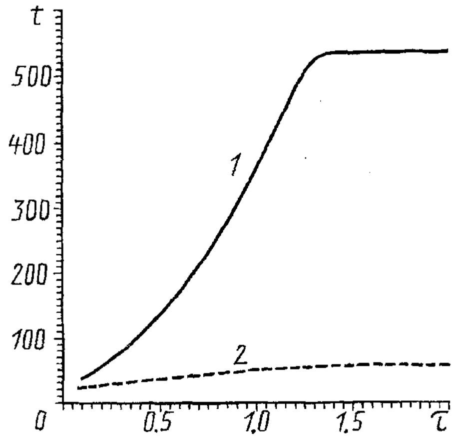
$$c\rho\left[\frac{\partial T}{\partial\tau} - \frac{d\zeta_1}{d\tau}\frac{dT}{\partial\bar{x}}\right] = \lambda\frac{\partial^2 T}{\partial\bar{x}^2}.$$

Hence it is easily seen that we may introduce two scales of time: $t^* = L^2c\rho/\lambda$ related with heat transfer by conduction and $t^{**} = c\rho L/v$ related with boundary motion. Since $t^{**} < t^*$, the boundary motion makes a large contribution to temperature field variation.

It should be emphasized that for the quasi-stationary case introduction of the moving coordinate system makes it possible to obtain simple analytical expressions for the temperature field in the tissue. The velosities of boundary motion $d\zeta_1/d\tau$ and $d\zeta_2/d\tau$ in this case are equal and time-independent

$$T = \frac{(T_1 - T_2)\exp\left(-\frac{v\bar{x}}{a_1}\right)}{1-\exp\left(-\frac{v\delta}{a_1}\right)} + \frac{T_2 - T_1\exp\left(-\frac{v\delta}{a_1}\right)}{1-\exp\left(-\frac{v\delta}{a_1}\right)},$$

$$a_1 = \lambda_1(c_1\rho_1)^{-1},\quad 0 < \bar{x} < \delta,$$



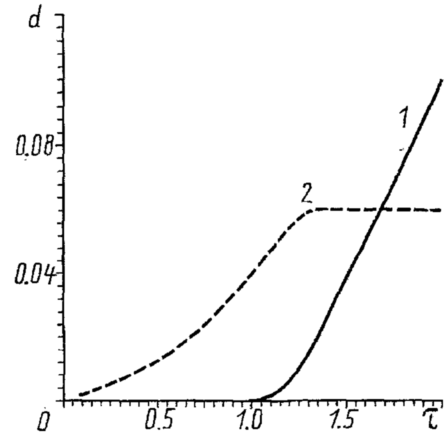


Fig. 1. Temperatures of phase boundaries t (°C) as a function of time) τ (sec):
1) t_1; 2) t_2.

Fig. 2. Time variation τ (sec) of motion of phase boundaries d (mm): 1) ζ_1;
2) $|\zeta_2 - \zeta_1|$.

$$T = \frac{T_2 \exp\left(-\frac{v\bar{x}}{a_2}\right)}{\exp\left(-\frac{v\delta}{a_2}\right)}, \quad \bar{x} > \delta, \quad a_2 = \lambda_2 (c_2\rho_2)^{-1}.$$

Here T_1, T_2, v, and δ are the constant functions of tissue thermophysical properties.

In the general case, Eqs. (1) through (6) are nonlinear and nonstationary. Based on the analysis of characteristic times of the process we may conclude that the characteristic time of the boundary motion is smaller than that of heat propagation in the body. Therefore the boundary conditions (3), (4) accounting for substance sublimation determine the temperature field principally, while Eqs. (1), (2) allowing for heat propagation by conduction only correct the results (smooth the temperature field). Now we transform boundary conditions (3), (4) to a form convenient for numerical calculations. For this, we replace the temperature derivatives by finite differences and take the logarithm of the expression obtained. As a result, for each time layer we have a system of two nonlinear equations for the temperatures of the phase boundaries T_1 and T_2:

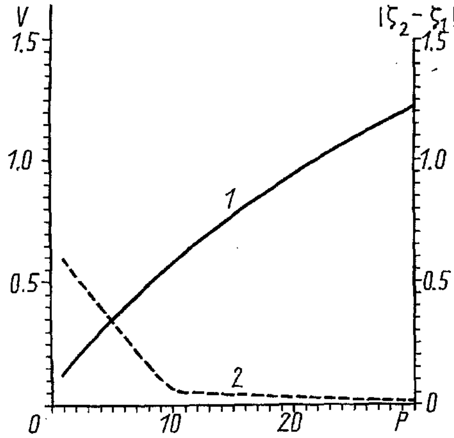
$$T_1 + \frac{L_1 A_1}{R \ln [(q + \lambda_1 \Delta T_1)(\rho_C L_1 a (1 - \Pi))^{-1}]} = 0; \tag{7}$$

$$T_2 + \frac{L_2 A_2}{R \ln \left[\left(1 + \frac{\delta}{2r}\right)(\lambda_2 \Delta T_2^+ - \lambda_1 \Delta T_2^-)(\Pi \rho_{H_2O} L_2 a)^{-1} \right]} = 0. \tag{8}$$

The temperatures T_i are found by solving the difference equations corresponding to the system of Eqs. (1)-(2) with the Dirichlet conditions at the boundaries:

$$c_1\rho_1 \left[\frac{T_n^j - T_n^{j-1}}{m} - a \exp\left(-\frac{L_1 A_1}{RT_1}\right) \frac{T_{n+1}^j - T_{n-1}^j}{2h} \right] = \\ = \lambda_1 \frac{T_{n+1}^j - 2T_n^j + T_{n-1}^j}{h^2}; \tag{9}$$

$$c_2\rho_2 \left[\frac{T_n^j - T_n^{j-1}}{m} - a \exp\left(-\frac{L_1 A_1}{RT_1}\right) \frac{T_{n+1}^j - T_{n-1}^j}{2h} \right] = \tag{10}$$



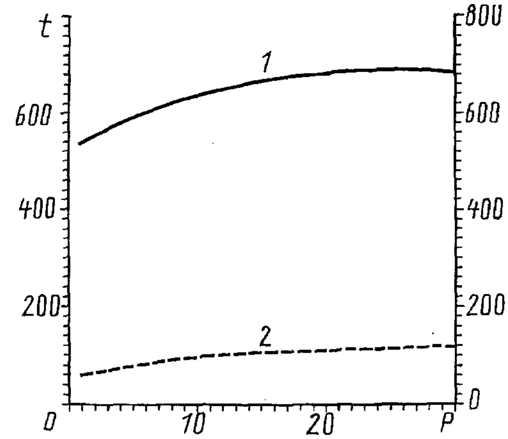


Fig. 3. Boundary velocity ζ_1/v, 10^{-4} m/sec (1) and interphase distance $|\zeta_2 - \zeta_1|$, $10^2\,\mu$m (2) versus supplied radiative power P, W.

Fig. 4. Temperatures of phase boundaries as a function of supplied radiative power: 1) t_1; 2) t_2.

$$T|_{\bar{x}=0} = T_1; \tag{11}$$

$$T|_{\bar{x}=\delta} = T_2. \tag{12}$$

The nonlinear system (7) through (12) is solved by the successive refinement method with respect to T_1 and T_2. On each refinement the temperatures $\{T_n^j\}$ are calculated from fresh solutions of the difference equations (9)-(12).

The positions of the boundaries ζ_1 and ζ_2 at each time step are found from relations (5), (6) using the implicit Euler scheme. In going to the next time step, the position of the boundaries and the network are rearranged. Thus, the nodes of the network are not fixed in time. To solve the nonstationary problem, it is necessary to know the temperature value at any points between the nodes; therefore use is made of the spline-interpolatio of the network function of the temperature of the previous time layer.

Solving the problem yielded temperature field distributions and dependences of the motion of the boundaries and the temperature of the phase fronts on time. The heat flux entering (3) is calculated in terms of the radiative power and the degree of its focusing. When a light guide is used to transfer radiation,

$$q = P(\pi R_0^2)^{-1}.$$

Figures 1 and 2 characterize the temperature variation of the boundaries and their motion with time for the radiation power P = 1 W and a light guide diameter of 400 μm. It is seen that tissue destruction proceeds in two steps: the first step involves heating and an increase of the temperatures T_1 and T_2 and the distance between phases δ. At this stage the processes are nonstationary; practically no material sublimation (motion of the boundary ζ_1) proceeds. At the second stage the problem may be treated as a quasi-stationary one. The boundary temperatures T_1 and T_2 and the distance between the phases are stabilized at certain values. Figures 3 and 4 represent the dependences of T_1, T_2, and δ on the supplied radiative power. The boundary motion acquires a linear character. Figure 3 depicts the boundary velocity ζ_1 as a function of the supplied power (with an increase of P the velocity increases logarithmically).

The time when the system comes to the quasi-stationary solution may be characterized by the relaxation time. For P = 1 W, $\tau \sim 1.3$ sec, while for P = 10 W, $\tau \sim 0.08$ sec. These quantities are given for an emissivity factor equal to unity, which corresponds to complete absorption of radiation at $T_1 < T_1^{st}$. With an account of the dependence $\varepsilon(T_1)$, τ will increase.

The results of solution of this problem are applicable for investigations in medicine and for optimization of the practice of using laser scalpels [11-13]. Of importance are such integral quantities as the relaxation time, the boundary velocity, and the interphase distance. The characteristic δ refers to the dimensions of the carbonization zone and, consequently, may serve for evaluation of the tissue necrosis zone. The velocity $\dot{\zeta}_1$ and the relaxation time characterize the effectiveness of lasers as applied for making incisions.

NOTATION

c_c, heat capacity of carbon; ρ_c, carbon density; λ_c, carbon thermal conductivity; c_{H_2O}, heat capacity of water; ρ_{H_2O}, water density; λ_{H_2O}, water thermal conductivity; λ_{air}, air thermal conductivity; τ, time; $\bar{x}$, coordinate in a moving system; x, coordinate in a fixed system; T, temperature; L_1, enthalpy of carbon sublimation; L_2, enthalpy of water vaporization; A_1, molecular mass of carbon; A_2, molecular mass of water; R, universal gas constant; a, sound velocity; P, radiative power; R_0, light guide radius; Π, tissue porosity; q, heat flux over a surface; r, radius of pores; ζ_1, phase boundary of air-carbon; ζ_2, phase boundary of carbon-tissue; T_1, temperature at the boundary ζ_1; T_2, temperature at the boundary ζ_2; δ, depth of the evaporation zone; v, destruction rate; T_n^j, network function of the temperature at the n-th node and at the j-th time step; h, mesh width used for a space variable; m, time step.

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