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Models of concentrated energy flux effects on homogeneous and porous media

O. G. MARTYNENKO, N. V. PAVLYUKEVICH, G. S. ROMANOV
and R. I. SOLOUKHIN

Heat and Mass Transfer Institute of the Byelorussian Academy of Sciences, Minsk, U.S.S.R.

Abstract—Physical and mathematical models of the processes accompanying the effect of strong radiation fluxes on homogeneous (metals) and porous media are described. For a homogeneous medium, the model describes the processes of heating and evaporation of the surface, unsteady-state axisymmetric expansion of vapours into the surrounding space and the motion thus induced of air displaced from the surface. At the absorbed energy flux densities of up to 10^2 W cm^{-2} the processes of transport of the directly emitted thermal radiation of vapours and air plasma become essential which lead, in particular, to additional heating and evaporation of the surface outside the region of primary radiation absorption. Calculations are carried out for the case of aluminum and bismuth surface irradiation by a neodymium laser operating in regular and irregular modes. For porous materials the characteristic feature is the formation of a volumetric heat source. The procedures for the description of radiation absorption in two models (capillary and globular) of porous media with an opaque skeleton are presented. Specific features of temperature fields in a porous plate exposed to constant and pulse-periodic radiation fluxes are discussed.

DESPITE a large number of studies in the field of laser radiation (LR) interaction physics and the diversity of the results obtained, the problems of the vapour generation dynamics and high-temperature vapour jet formation on the surface are still of importance in the study of the moderate intensity laser radiation effect on condensed media.

To a greater extent the foregoing applies to the problem of LR interaction with capillary-porous and polymer materials in conditions that lead to their heating and thermal, as well as mechanical, destruction. The present paper will set forth some results of the authors' investigations in these trends.

Earlier theoretical models [1–3], that ignored the presence of atmosphere around a barrier and an inhomogeneous character of vapour and plasma motion at the surface, have encountered a variety of unexplained phenomena and quantitative discrepancies with actual experimental data. Even a qualitative understanding of the sequence of phenomena observed was extremely aggravated by a complex temporal structure of LR pulse typical of irregular generation [1–4]. Subsequent experiments with lasers operating in the mode of regular microsecond pulses (with the total duration of generation of the order of 1 ms) have provided a qualitative picture of radiative–gasdynamic processes in a laser erosive plasma torch (LEPT) [5–11]. Experiments with microsecond monopulses [12, 13], together with a computational model developed in refs. [14, 15], have furnished an understanding of qualitative and quantitative trends in laser plasma plane flow at the target surface, and have made it possible to substantiate quantitatively the concepts [13–15] of the modes of displacement, subsonic radiative wave and of the supersonic radiative wave which replaces the detonation mode. The concepts of these modes, each characteristic of a certain region of the LR energy flux density variation, lead to a deeper understanding of the variety of processes observed at the target exposed to radiation pulses with a complex temporal structure both in the case of a one-dimensional (plane) geometry of plasma flow and in a two-dimensional (axisymmetric) one taking place at rather large times. A theoretical study of the effects of the two-dimensional nature of motion, indispensible for a limited area of irradiated target surface, was undertaken much later than the respective experiments [5, 6]. However, just as in the earlier works [16–18], so in subsequent research [19–21] the results obtained testified to agreement with the experiment. Below, we will describe the available computational model and will cite the results to compare with experimental data.

The experimental data refer to the cases of the irradiation of metals by neodynium lasers operating in regular and irregular modes [22–25], as well as some cases of LR of quasi-continuous pulses and microsecond monopulses [12, 13, 26–28].

When studying the effect of radiative fluxes on porous media, attention is mostly paid to the radiation absorption and temperature fields inside a body that determine the dynamics of heat and mass transfer processes in porous materials. Therefore, the development of procedures for describing radiation absorption in different models of porous bodies, and the determination of temperature fields in different modes of exposure is a problem of practical importance.

NOMENCLATURE

a	thermal diffusivity of metal
c	speed of sound
E	total energy of gas per unit mass
E_i	exponential integral functions ($i = 1, 2, 3$)
H	enthalpy
L	plate thickness
p	pressure
q	density of radiation energy flux
r, z	radial and axial coordinates
S	thermal radiation energy flux
u	radial velocity component, $= w_r$
v	axial velocity of vapours in the gas dynamics problem; velocity of the boundary of evaporation in the thermal problem, $= w_z$
V	volume
w	velocity of vapours.

Greek symbols

ε	thermal energy of gas per unit mass; energy of a photon and material emissivity
κ_j	coefficient of radiation absorption with frequency ν in plasma
λ	specific energy of evaporation; mean free path of photon
λ_o	wavelength of absorbed radiation
ψ	porosity
ρ	medium density
σ	Stefan–Boltzmann constant.

COMPUTATIONAL MODEL OF THE LASER EFFECT GASDYNAMICS [17–21, 29]

To describe the target surface heating and evaporation by incident radiation, the motion of vapours capable of absorbing radiation, losing energy into the surroundings by radiative cooling, transmitting their kinetic energy to the surrounding gas with account for its shock compression, and the motion of a shock-compressed gas also capable of absorbing incident radiation and losing its thermal energy by emission, it is necessary to solve self-consistent thermal (for the target) and radiative–gasdynamic (for vapours and atmospheric gas set in motion) unsteady-state problems. Their connection seems to be attained by means of boundary conditions which couple the radiative energy flux incident on the surface with the energy fluxes transported into the target by heat conduction, and into the gas phase by evaporation.

Assuming LR to fall on a circular area of radius r_o on a target, we can formulate the thermal and gasdynamic problems in the cylindrical system of coordinates with the axial symmetry.

Consider first the problem of heating and evaporation of the surface by a cylindrical radiation beam of frequency ν and radius r_b incident on the surface along the axis z. The initial density of the energy flux from a source far from the barrier is $q_\infty^-(r, \infty, t)$, and flux density on the surface, $q_o^-(r, 0, t)$, is determined by radiation absorption in the torch. The absorbed portion of the flux density $q_s = [1-R(T_o)]q_o^-(r, 0, t)$ [where $R(T_o)$ is the coefficient of the reflection of radiation of frequency v by the surface at temperature T_o] heats and then vaporizes the barrier, and these processes are described by the boundary-value heat conduction problem [4]:

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial z^2} + v\frac{\partial T}{\partial z}$$

$$-\lambda\frac{\partial T}{\partial z}\bigg|_{z=0} = q_s - \rho_o v \Delta H \tag{1}$$

$$T(z, r, 0) = T_{oo}$$

where T is the temperature, a is the thermal diffusivity, λ the thermal conductivity, ρ_o the target density, v the evaporation wave velocity, and ΔH the difference of the enthalpies of the gas and condensed medium. In equations (1), the quasi-one-dimensional approximation is adopted, i.e. it is assumed that within the irradiated surface, $r = r_b$, the heating along the axis z is determined only by the value of $q_s(r, t)$.

Using the method of moments to solve the system of equations (1) and restricting ourselves to two first moments along the coordinate z (in this case the temperature of the heated layer T_o is assumed to be constant over the layer thickness z_o), we obtain the system of equations for two unknown quantities T_o and z_o:

$$\frac{dT_o}{dt} = \frac{3}{3\sqrt{\pi}}\left[\frac{2a}{\lambda z_o}(q_s - \rho_o v\,\Delta H) - \frac{2a}{z_o^2}(T_o - T_{oo})\right],$$

$$\frac{dz_o}{dt} = \frac{\sqrt{3\pi}}{4}\left[-\frac{a}{\lambda T_o}(q_s - \rho_o v\,\Delta H) - v + \frac{2a}{z_o T_o}(T_o - T_{oo})\right]. \tag{2}$$

Here the derivatives dT_o/dz and dz_o/dt are determined in such a way that, together with the correct rate of heating in the absence of evaporation [$T_o =$

$2q\sqrt{at}/(\lambda\sqrt{\pi})$], the equality should hold between the absorbed energy and the energy contained in the heated layer.

The quantities v and ΔH in equation (2) are determined by solving the gas kinetic problem for the parameters of vapours at the outer boundary of the Knudsen layer similarly to ref. [4] accounting for the fact that the velocity $\bar{u}$ of the vapours at the surface $0 \leqslant \bar{u} \leqslant \bar{c}$, where $\bar{c}$ is the speed of sound.

The system of finite-difference equations corresponding to the set of equations (2), together with the expressions for v and ΔH, is solved numerically on each time layer when solving the following gas-dynamic problem.

The half-space $z > 0$ is initially filled with air with a pressure p_{in} and density ρ_{in}, being transparent for radiation. The motion induced by the vapours formed at $\bar{p} > p_{in}$ is described by the system of gasdynamic equations

$$\frac{\partial \rho}{\partial t} + \operatorname{div}(\rho \vec{w}) = 0$$

$$\frac{\partial \rho u}{\partial t} + \operatorname{div}(\rho u \vec{w}) + \frac{\partial p}{\partial z} = 0$$

$$\frac{\partial \rho v}{\partial t} + \operatorname{div}(\rho v \vec{w}) + \frac{\partial p}{\partial r} = 0$$

$$\frac{\partial \rho E}{\partial t} + \operatorname{div}(\rho E \vec{w}) + \operatorname{div}(p \vec{w}) = \frac{\partial q^-}{\partial z} + \frac{\partial q^+}{\partial z} - \sum_k Q_k + \sum_k \operatorname{div} \bar{S}_k \quad (3)$$

$$p = p(\rho, \varepsilon).$$

Here Q_k is the energy lost by plasma in the kth spectral range due to the bremsstrahlung and photoconductive processes, S_k is the radiant flux density of the torch in the kth spectral range; the rest of the symbols are conventional. The density of the laser radiation energy flux directed to the surface, q^-, and reflected from it, q^+, are equal to

$$q^-(r, z, t) = q_\infty^-(r, \infty, t) \exp\left(-\int_z^\infty \kappa'_\nu \, dz'\right),$$

$$q^+(r, z, t) = q_0^-(r, 0, t) R(T_0) \exp\left(-\int_0^z \kappa'_\nu \, dz'\right)$$

where κ'_ν is the plasma absorption coefficient at the frequency corrected for stimulated emission.

When calculating the transport of the self-emission of the torch, its spectrum is usually subdivided into three spectral groups inside of which the absorption coefficient is assumed to be independent of the frequency and to be coincident with the Planck-averaged one [30] within the boundaries of the spectral group. To calculate the transport of radiation, the two-flux approximation is used along each coordinate r and z:

$$\operatorname{div} \bar{S}_k = \frac{\partial}{\partial z}(S_{kz}^+ - S_{kz}^-) + \frac{1}{r}\frac{\partial}{\partial r}(rS_{kr}^+ - rS_{kr}^-)$$

where $S_{kz,r}^\pm$ are the energy fluxes in the kth spectral group determined by absorption, in the positive and negative directions of the axes z and r. The difference presentation of this expression has the form (i, j are the numbers of cells along the axes z and r):

$$(\operatorname{div} S_k)_{i,j} = (S_{ki+1,j}^- + S_{ki-1,j}^+)\frac{1 - \exp(-\bar{\kappa}_{ki,j}\Delta z)}{\Delta z}$$

$$+ \left(\frac{r_{j-1/2}}{r_j \Delta r} S_{ki,j-1}^+ + \frac{r_{j+1/2}}{r_j \Delta r} S_{k,i,j+1}^-\right)(1 - \exp(-\bar{\kappa}_{ki,j}\Delta r))$$

where $\bar{\kappa}_k$ are the Planck-averaged absorption coefficients in the kth spectral range. The density of the thermal radiation flux $S_{ki,j}^+$, emerging from the cell i, is

$$S_{ki,j}^+ = q_{ki,j} + S_{ki-1,j}^+ \exp(-\bar{\kappa}_{ki,j}\Delta z)$$

where $q_{i,j}$ is the density of the thermal radiation flux from the cells along the axes z and r, for which the following expressions are used

$$q_{kz,z} = \begin{cases} L_{kr,z}\beta_k, & L_{kr,z} = \bar{\kappa}_k \Delta r, \quad \Delta z \leqslant 1 \\ \beta_k & L_{kr,z} > 1 \end{cases}$$

$$\beta_k k = \int_{\varepsilon_k}^{\varepsilon_k^2} B_\varepsilon \, d\varepsilon, \quad B_\varepsilon = \frac{15}{\pi^4}\frac{6\varepsilon^3}{(e^{\varepsilon/T} - 1)}.$$

The radiation losses for the k-spectral group have the form

$$Q_{ki,j} = 2(q_{ki,j}\Delta_i + q_{ki,j}\Delta_j)/V_{ij}$$

where Δ_i and Δ_j are the areas of the base and side surfaces of the cell, V_{ij} is the cell volume. This description provides the continuity of transition from volumetric to black-body radiation.

The pressure or density of saturated vapours, in terms of which the pressure and density of vapours at the surface are determined, are prescribed as functions of T_0. For the vapour state equation $p = p(\rho, \varepsilon)$, required to solve the set of equations (3), the tables used are compiled by solving the full system of equations for the dissociated and ionized equilibria [30]. The absorption coefficients κ'_ν and $\bar{\kappa}_k$ take into account the line bremsstrahlung absorption (calculated according to Kramer's methods), and photoelectric absorption (calculated by the quantum defect technique). The procedure of such calculations is described elsewhere [32]. For the air state equation the tables which are used have been compiled from the data of ref. [33], the optical characteristics of air are taken from ref. [34].

The absorption coefficients of the aluminum plasma and air at the emission wavelength $\lambda_0 = 1.06$ μm are presented for different densities ρ as functions of temperature. A preliminary analysis of these data, together with the solution of the gasdynamic problem on LR effect, makes it possible to find out the role of absorption for this or other cases.

When calculating radiation transfer, the boundaries of the spectral groups are thus selected so as to take into account the energy losses by torches due to the cold air transparency within the range of energies up to 6.52 eV and the cold air heating ahead of the hot plasma front by continuous spectrum radiation from the hot region in the spectral ranges 6.52–10 eV and 10–100 eV. This subdivision corresponds to the qualitative behaviour of the aluminum plasma and hot air absorption coefficients. The accuracy of description of the spectral energy transport in the torch may be increased by a more detailed resolution of the spectrum by increasing the number of the groups of lines. In the case of a fixed computer memory volume this may lead to the loss of accuracy in the description of the flow gasdynamic structure details due to a smaller number of nodes of the grid. In our case this number amounts to about 2000 nodes.

For the solution of the set of equations (3), the method of 'large particles' [37] is employed, extended to the case of a non-adiabatic plasma flow accompanied by the processes of radiation absorption and transport. Separate description of the opticophysical parameters of the barrier vapours and air is achieved by introducing the contact interface with the aid of tracers (passive particles) moving with the velocity equal to that of the gas at the place of particles location.

The boundary conditions on an evaporating surface are obtained by solving problem (2) with the radiation flux density equal to

$$q_s = [1-R(T_o)]q^-(r,0,t)+\sum_k S^-_{kr}(r,0,t).$$

For an impermeable wall and symmetry axis the non-flow conditions are employed. On the approach of gasdynamic perturbations to one of the computational grid boundaries, its extension is made in this direction by twice increasing the size of its meshes. In some cases the grid may not be reconstructed. Thus, in a number of cases it is possible to model numerically the main specific features of radiative–gasdynamic processes in metals exposed to LR [17–21, 29, 31].

We shall give some results of calculations for the case of neodymium laser radiation ($\lambda_o = 1.06\ \mu$m) on aluminum and bismuth targets. (The effects of one pulse of length $\tau = 1\ \mu$s, of a series of microsecond pulses and of a smooth pulse of millisecond duration on targets in air at a pressure of 1 atm were considered.)

Due to the absorbed laser energy, the metal surface is heated rapidly (for the time of about 10^{-9}–10^{-6} s) up to the temperatures at which an intensive evaporation of substance starts. The time of the start of evaporation preceding the plasma formation depends on the LR flux density, surface reflection coefficient and thermophysical characteristics of the substance [30]. Experimentual investigations show that at the given shape and length of the laser pulse there is an LR flux density q_e at which the substance starts to evaporate. As the conventional point for the start of intensive evaporation, the temperature condition is used at which the pressure of the target material saturated vapours rises above that of the surrounding atmosphere (under normal conditions this is the temperature of boiling). In the free lasing mode, for the majority of metals q_e is confined within the range 10^5-10^7 W cm^{-2} [30]. When $q > q_e$, there occurs an intensive evaporation of the metal and plasma formation due to LR absorption in the forming, slightly ionized vapours at free–free transitions of electrons in the field of ions and neutral atoms. As follows from the plots of the absorption coefficients in Fig. 1, their distinctive feature is a sharp dependence on

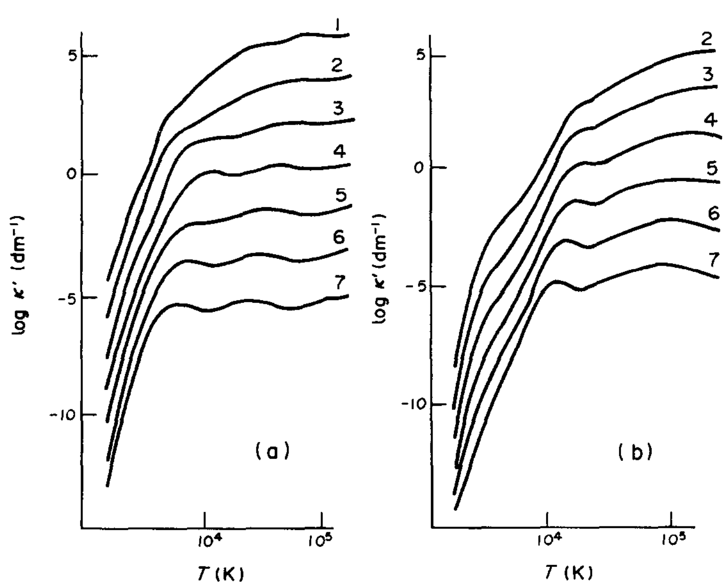

FIG 1. Monochromatic absorption coefficients $\lambda_0 = 1.06\ \mu$m of aluminum vapours (a) and hot air (b): 1, $\rho = 10^{-1}$ g cm^{-3}; 2, $\rho = 10^{-2}$ g cm^{-3}, ..., 7, $\rho = 10^{-7}$ g cm^{-3}.

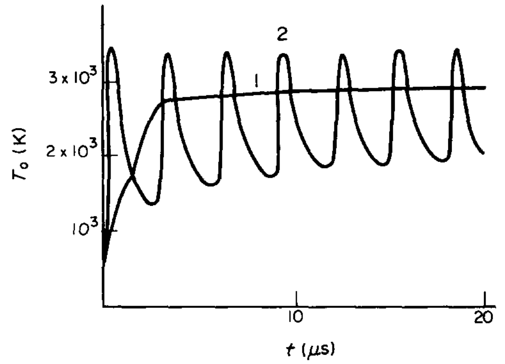

FIG 2. Surface temperature of a bismuth target depending on time: 1; constant flux density, $q = 2$ MW cm^{-2}; 2, 1-μs-long radiation pulses, spacing between pulses is 3 μs, $q_{max} = 12$ MW cm^{-2}.

temperature in the region of first ionization. Here, a higher potential of air ionization, as compared with the corresponding potential of the target material ionization, is responsible for a much lower absorption coefficient. From this it follows that in the case of a moderate LR intensity the plasma should first appear in the target vapours. Already the first experiments on laser radiation effect have shown that LR of moderate intensity ($q \sim 10^6$–10^7 W cm^{-2}) is a convenient means for obtaining a low-temperature erosive plasma [1, 5–8].

In the case of the exposure of metals to LR of millisecond pulses (the modes of irregular, regular and quasi-continuous generation), erosive plasma torches are formed which have a complex gasdynamic structure due to the under-expanded escape and interaction of successively moving shock waves with the plasma torch and surroundings [6–11, 23–25].

A two-dimensional, numerical simulation of the processes occurring during the exposure of metals to LR of millisecond pulses (quasi-continuous and regular generations), when the effects of two-dimensional motion are substantial and the LEPT has the character of a non-adiabatic plasma jet, has made it possible to reveal a number of specific features in the dynamics of LEPT which correspond to the actual experiments. As a whole, the picture of LEPT formation in the case of steady-state and spiking LR pulses differ qualitatively. The dynamics of LEPT formation is well followed from the axial density profiles (Figs. 3a,b). In the both cases, by the time $t = 20$ μs, a direct shock wave has time to form at a distance of about 4 mm from the target surface; this is in agreement with the experimental results [36]. Calculations show that in spite of a great difference in pressures on the target surface (in the spiking mode the maximum pressure is about 200 atm and in the quasi-steady mode it is about 45 atm), the shock wave location depends weakly on the mode of effect.

In the spiking mode, as compared with the steady-state, there are usually higher temperatures behind the direct shock wave. However, in spite of relatively high temperatures, a denser surface plasma is heated in this mode (Fig. 3b), but the direct shock wave does not lead to the surface screening due to a relatively small density of erosive plasma in it (Fig. 3b).

The results of numerous calculations on the effect of single 1-μs-long LR pulses on metal barriers are described in detail in refs. [19–21, 31, 36]. It follows from these calculations that there is a satisfactory agreement between the theoretical and experimental data on the surface temperature, recoil pulse acting on the barrier, quantity of energy lost by the torch by emission into the surroundings, quantity of mass

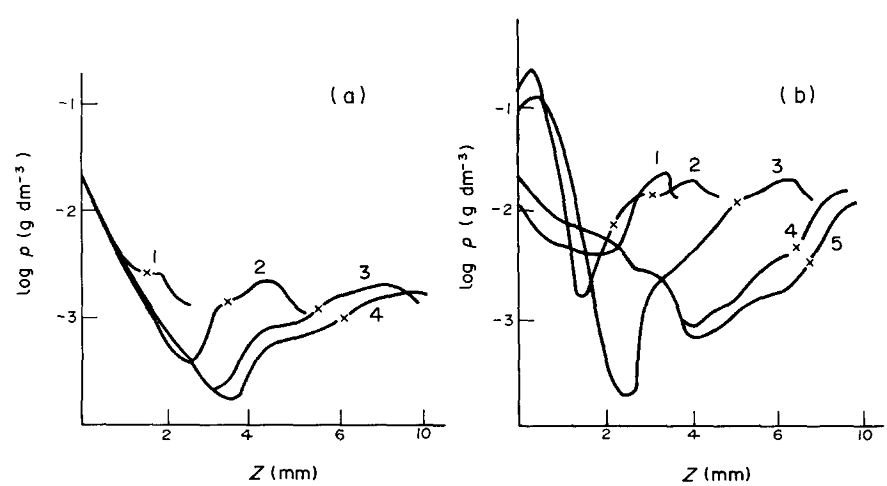

FIG. 3. Density on the jet axis vs the distance to the bismuth barrier. ×—location of the contact boundary between vapours and a compressed air. (a) Constant flux density q: 1, $t = 5$ μs; 2, $t = 10$ μs; 3, $t = 17$ μs. (b) Pulse effect 1, $t = 3.9$ μs; 2, $t = 5$ μs; 3, $t = 10$ μs; 4, $t = 17$ μs; 5, $t = 20$ μs.

evaporated before the incipience of surface screening by the generated plasma and other characteristics. The spatial–temporal distributions of the gasdynamic parameters of the originating motion are also described satisfactorily. Note further that in spite of the fact that a two-dimensional numerical simulation gives, on the whole, a good agreement with the observed physical picture in actual experiments, it does not as yet allow such effects as the formation of successively moving shock waves, multiple compression of air, turbulence in the torch and a number of other finer details of the flow to be revealed.

Effect of radiation on porous media

A characteristic feature of the effect of radiative fluxes on porous materials is the formation, in a body, of a volumetric thermal source which may exert a substantial effect on the temperature field in the material, especially at small times of the effect and also on the processes of its destruction in the zone of irradiation.

For the description of the processes of transport in porous media, a certain physical model of a porous body is used. Depending on the structural features and the level of porosity, either a capillary or a globular model is used which can be either regular or stochastic. Thus, among the capillary models the simplest one is a system of parallel, cylindrical capillaries of the same radius. The globular models are most often used in application to highly dispersed bodies with sufficient porosity.

To accumulate the solar energy, specially prepared porous film coatings are used with nearly parallel capillaries oriented normally to the irradiated surface [37] and for insulation—the materials with randomly oriented cylindrical fibres [38].

In the case of radiative drying of capillary-porous materials, there occurs volumetric absorption of infrared radiation; then in the material irradiated, dry and moist zones are formed which are separated by a moving zone (surface) of evaporation [36]. In this case, to state correctly the heat and mass transfer problem, it is necessary to know the internal heat sources which are determined with account for absorption of radiation penetrating into the material.

The experimental study of laser radiation effect on porous materials, obtained by the method of powder sintering, was the concern of ref. [40] in which it was noted that the role of porosity in the accounting for an increase of the effective depth of radiation penetration into the material increases the fraction of energy spent for the substance heating and destruction.

In ref. [41], based on the solution of the problem of radiant energy absorption in a non-isothermal cylindrical channel of finite length, an approximate analytical expression has been obtained for a thermal source distributed over the depth of a porous body (with a non-transient skeleton) modelled by a system of parallel capillaries. It should be noted that only in a particular case of $\varepsilon = \varepsilon_1 = 1$ (ε, ε_1 are the emissivities of the side and bottom surfaces of the capillary) this expression is an exponential function (i.e. of Bouger type).

The solution of the heat conduction problem in a porous plate of thickness L, exposed to a pulsed-periodic radiative flux, with the use of the expression obtained earlier for a volumetric source allows the following conclusions to be drawn [42].

During the pulse action (and when $t < \tau_T = L^2/a$) the surface temperature $T_w(t)$ of a porous body with a distributed heat source, $I(x)$, is smaller than that in the surface source approximation for any ε. However, after a certain period of time, on the termination of the effect of each pulse, when $\varepsilon < 1$, it starts to exceed T_w in the surface source approximation. For $\varepsilon = 1$, T_w becomes virtually equal in the both cases, although both decrease at the end of the period. For comparison note that in the steady-state problem for ε close to unity the heating surface temperatures T_w in the mentioned cases are nearly the same, but for small εs may differ substantially.

For the body section $x = 0.2$, in contrast to the above-considered heating of the surface $x = 0$, the heating continues for some time after the termination of each pulse and then the cooling begins up to the start of the next pulse. For small εs these temperature fluctuations are characterized by smaller amplitudes. That the inner source is distributed is evident from the fact that at small εs the temperature in this section for all ts exceeds the temperature in the case of the surface source. For $\varepsilon = 1$, the above-mentioned temperatures differ virtually only in the time intervals corresponding to the growth of temperature in the plane $x = 0.2$.

For the values of x closer to the lower boundary of the plate, $x/L = 1$, the temperature of these body layers actually increases with the time during the whole process, i.e. the above-mentioned temperature fluctuations decay in time constantly on approaching the lower boundary of the body, $x/L = 1$; at the end of each cooling period the body temperature becomes constant for all xs. In this case, for $\varepsilon < 1$ the difference is preserved between the body temperature and the corresponding temperature in the surface source approximation.

Thus, at small times ($t < \tau_T$) the distributiveness of the absorbed radiation energy over the porous body depth may exert a noticeable effect on the character of temperature field near the heating surface $x = 0$. At large times (and in the case of the steady state) the effect of $I(x)$ is observed only for $\varepsilon < 1$, while for $\varepsilon < 1$ the source may be considered as the surface one. A porous body is capable of accumulating the radiant energy to a greater extent than a solid body at the same values of ε, and the effective absorptivity of a porous body increases with a decreasing ε and increasing porosity. At the same time, on the cessation of the external source the self-emission of the surfaces of capillaries favours the porous material cooling.

The calculation of radiative heat transfer in layers of randomly packed spheres [43–46] is carried out, as a rule, with the use of the effective absorption and scattering coefficients. However, for highly porous bodies with a non-transparent skeleton, it is possible, by using the globular model, for radiation energy emerging from a unit volume of a porous body per unit time, to set up the integral equation which takes into account the body structure and the multiplicity of scattering:

$$\phi(x) = \varepsilon S\sigma T^4(x) + (1-\varepsilon) \times \left[\psi q_o K(x/\lambda)\frac{1}{\lambda} + 2q_1 E_2\left(\frac{L-x}{\lambda}\right)\frac{1}{\lambda} + \frac{1}{2}\int_0^L \phi(\xi) E_1\left(\frac{|x-\xi|}{\lambda}\right)\frac{1}{\lambda}\mathrm{d}\xi \right],$$

where q_o is the external radiation flux density, $\lambda = 4\psi r/[3(1-\psi)]$ is the mean free path of photons, ψ the porosity, $S = 3(1-\psi)/r$ the surface area of non-transparent spherical particles of radius r per unit volume of the body modelled by a homogeneous system of such randomly distributed spheres. Here, for a collimated source $K(x/\lambda) = \exp\{-x/\lambda\}$, for a diffusive one $K(x/\lambda) = 2E_2(x/\lambda)$; E_i are the exponential integral functions which are replaced by exponentials [47] on finding an approximate solution. The density of the radiation flux from the lower boundary of the layer $x = L$ is

$$q_1 = \psi\varepsilon\sigma T_1^4 + (1-\varepsilon)\left[\psi q_o K'(L/\lambda) + \frac{1}{2}\int_0^L \phi(\xi)\left(\frac{L-\xi}{\lambda}\right)\mathrm{d}\xi \right]$$

where $K' = 2E_3(L/\lambda)$ for a diffusive source and $K' = \exp\{-L/\lambda\}$ for a collimated source.

An approximate solution of the problem of radiation passage through a porous layer makes it possible to determine the fraction of radiation absorbed and reflected by the layer, the distribution of the density of the absorbed energy power ϕ^* for both diffusive and collimated external sources. In particular, for $q_o \sim \sigma T_w^4$, ϕ^* can have a local maximum not only for a collimated, but also for a diffusive source (with account for the non-isothermal nature of the layer); at the same time for $q_o \gg \sigma T_w^4$, ϕ^* is most often a monotonically decreasing function.

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MODELES DES EFFETS DES FLUX D'ENERGIE CONCENTRE SUR LES MILIEUX HOMOGENES ET POREUX

Résumé—On décrit des modèles physiques et mathématiques des mécanismes qui accompagnent l'effet des flux de rayonnement élevés sur des milieux homogènes (métaux) et poreux. Pour un milieu homogène, le modèle décrit les mécanismes de chauffage et d'évaporation à la surface, la dilatation variable axisymétrique des vapeurs dans l'espace environnant et le mouvement ainsi induit d'air déplacé depuis la surface. Jusqu'à des densités de flux énergétique de 10^2 W cm^{-2}, les mécanismes de transfert du rayonnement thermique directement émis par les vapeurs et le plasma d'air deviennent essentiels et conduisent, en particulier, à un chauffage et une évaporation additionnels depuis la surface, hors de la région de l'absorption de rayonnement primaire. Pour des matériaux poreux le point caractéristique est la formation d'une source volumique de chaleur. Les procédures pour la description de l'absorption du rayonnement dans deux modèles (capillaire et globulaire) des milieux poreux avec un squelette opaque sont présentées. On discute des particularités des champs de température dans une plaque poreuse exposée à des flux constants ou périodiquement pulsés.

MODELLE ZUR BESCHREIBUNG DER KONZENTRIERTEN BESTRAHLUNG HOMOGENER UND PORÖSER STOFFE

Zusammenfassung—Es werden physikalische und mathematische Modelle vorgestellt, welche die bei starker Strahlungsbeaufschlagung homogener (Metalle) und poröser Stoffe auftretenden Begleiteffekte beschreiben. Im Fall eines homogenen Mediums beschreibt das Modell die Erwärmung und die Oberflächen-Verdampfung, die instationäre asymmetrische Ausbreitung von Dämpfen in die Umgebung und die daraus resultierenden Luftbewegungen. Bei den absorbierten Strahlungsdichten von bis zu 100 W cm^{-2} erlangen die Transportvorgänge aufgrund direkt emittierter Wärmestrahlung von Dämpfen und Luft–Plasma wesentliche Bedeutung, wodurch insbesondere Oberflächenteile, die nicht im primären Absorptionsbereich liegen, verstärkt erwärmt und verdampft werden. Die Bestrahlungsvorgänge an Aluminium- und Wismutoberflächen mit einem Neodym-Laser werden berechnet. Wesentlichster Gesichtspunkt bei der Beschreibung der Vorgänge bei porösen Medien stellt die Definition einer volumetrischen Wärmequelle dar. Die Strahlungsabsorptionsvorgänge in zwei porösen Stoffen unterschiedlicher Materialstruktur (kapillarer und kugelförmiger Aufbau) werden an einem lichtundurchlässigen Strukturmodell beschrieben. Die spezielle Form der sich ausbildenden Temperaturfelder in porösen Platten bei konstanter und pulsperiodischer Strahlungsbeaufschlagung wird diskutiert.

МОДЕЛИ ПРОЦЕССОВ ВОЗДЕЙСТВИЯ КОНЦЕНТРИРОВАННЫХ ПОТОКОВ ЭНЕРГИИ НА ОДНОРОДНЫЕ И ПОРИСТЫЕ СРЕДЫ

Аннотация—Описаны физические и математические модели процессов, сопровождающих воздействие мощных потоков излучения на однородные (металлы) и пористые среды. Для однородной среды модель включает в себя описание процессов нагрева и испарения поверхности, нестационарного осесимметричного случая расширения паров в окружающее пространство и вызванное им движения оттесняемого от поверхности воздуха. При плотностях потока поглощаемой энергии до 10^2 Вт/$см^2$ существенными оказываются процессы переноса собственного теплового излучения паров и плазмы воздуха, которые, в частности, приводят к дополнительному нагреву и испарению поверхности вне области поглощения первичного излучения. Расчеты проведены для случая воздействия одиночных и повторяющихся импульсов излучения неодимового лазера на поверхность алюминия и висмута. Для пористых материалов характерным является образование объемного теплового источника. В работе приведены методики описания поглощения излучения для двух моделей пористых сред с непрозрачным каркасом: капиллярной и глобулярной. Обсуждаются особенности температурных полей в пористой пластине при воздействии на нее постоянного и импульсно—периодического потоков излучения.