GASDYNAMIC PROCESSES IN HEATING OF A SUBSTANCE BY LASER RADIATION

(GAZODINAMICHESKIE PROTSESSY PRI NAGREVANII VESHCHESTVA IZLUCHENIEM LAZERA)

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Processes of heating and gasdynamic motion of substances under the action of strong laser radiation are studied. The case of heating of a transparent mass of gas is examined. Also the problem of heating by radiation of an initially cold and stationary gas occupying a volume adjacent to a vacuum is solved.

The existence of self-similar state of flow is pointed out. Results of self-similar solution and numerical calculations are presented and compared.

The possibility is discussed to use the obtained results for describing the heating and vaporization of material from the surface of a solid body in the case of action of strong laser radiation with modulated streangth.

In connection with investigation of the possibility of heating metrial to high temperatures by laser radiation with modulated strength, recently the examination of a number of gasdynamic problems is of substantial interest which take place on focusing the radiation on the surface of condensed media. The gasdynamic approach to the solution of indicated problems is dictated by the circumstance that for sufficiently powerful fluxes of laser radiation the temperature increase is associated with an initiation of gasdynamic motion of material ("vaporization"), which in turn exerts substantial influence on the entire process of heating. An essential peculiarity of the process under examination, which complicates the solution of the problem, is the dependence of the absorption power on the state of the substance in its gasdynamic motion.

Indeed, if the absorption coefficient per unit mass is a constant value, then the main part of the incident flux is absorbed in a layer of approximately constant mass with optical thickness ~ 1, and in this case it is not dependent on the state of the substance. However, if the coefficient of absorption depends on the density and temperature, which is realized for example in an ionized gas, then the optical density of the substance strongly depends on the distribution of gasdynamic quantities. In the latter case equations of radiation transfer become substantially more complicated because of dependence on gasdynamic quantities.

Gasdynamic motion was taken into consideration for heating by laser radiation of small volumes of material with constant mass in [1 and 2]. However, in all these papers gasdynamic equations were not examined. The motion of matter was described by means of quantities averaged over the volume. Heating of matter with varying mass without taking into account gasdynamic motion was examined in [3]. In papers [4 and 5] gasdynamic motion was examined for a given mass of material the optical thickness of which was much smaller than one, while the absorption depended on temperature and density.

One-dimensional gasdynamic problem of heating of material is examined below for the case of incident strong monochromatic laser radiation on the surface of gas which is initially cold and immobile and which prior to heating fills a halfspace adjacent to a vacuum. The special feature of the problem examined is, in distinction from those mentioned above, the exact solution of gasdynamic equations in case of changing mass which is included by the motion in the process of action of a laser radiation pulse.

The solution of such a problem can be used for approximate description of the process of vaporization and heating of a solid substance placed in a vacuum under the action of laser radiation.

1. Equations of motion, continuity, energy and transfer of radiation in the planar case have the following form in Lagrangian mass coordinates:

$$\frac{\partial u}{\partial t}+\frac{\partial p}{\partial m}=0, \qquad \frac{\partial v}{\partial t}-\frac{\partial u}{\partial m}=0, \qquad \frac{\partial e}{\partial t}+p\frac{\partial v}{\partial t}=-\frac{\partial F}{\partial m}, \qquad \frac{\partial F}{\partial m}=-KvF \tag{1.1}$$

Here u is the velocity, p is the pressure, v is specific volume, e is internal energy per unit mass, F is the radiation flux, K is the absorption coefficient and m is the mass coordinate.

At the initial instant the substance fills the halfspace $m > 0$ $(x > 0)$ and is cold $(e = 0)$ and immobile $(u = 0)$. At $t > 0$ radiation flux F_0 falls on the substance from the vacuum side. The initial and boundary conditions thus have the form

$$F = u = p = 0, \qquad v = v_0 \qquad \text{for } m > 0, \quad t = 0 \tag{1.2}$$

$$p = 0, \qquad F = F_0 \qquad \text{for } m = 0, \quad t > 0$$

We shall assume that the coefficient of absorption K is a power function of internal energy e and density ρ

$$K = ae^{\beta}\rho^{\alpha}$$

For fully ionized plasma, for example, $\alpha = 2$ and $\beta = -{}^{3}/_{2}$. It is apparent that for such a coefficient of absorption an increase in temperature and expansion of gas lead to a decrease of absorption of heated and rarefied layers and to a deeper penetration of radiation.

Let us examine the process of heating of material by radiation. For simplicity in this connection we shall assume that the substance is a gas with an equation of state $e = pv(\varkappa - 1)$, where $\varkappa$ is the adiabatic index. The expression presented above for the absorption coefficient is applicable over the entire range of densities and temperatures.

At first let us determine the maximum temperature which can be obtained on heating of a plane transparent layer of gas of fixed mass m^0. The energy equation in this case has the form

$$\frac{\partial e}{\partial t}+p\frac{\partial v}{\partial t}=KvF_0 \tag{1.3}$$

From this we have the following expression for internal energy at some point before arrival of rarefaction wave at that point

$$e(t) = \left[\frac{5}{2}\, a v_0^{-1} F_0 t\right]^{2/5} \qquad (1.4)$$

The wave propagation time of rarefaction over the distance x is equal to

$$x = \int_0^t c\,dt = \frac{5}{6} \sqrt{\varkappa(\varkappa-1)} \left[\frac{5}{2}\, \frac{a}{v_0}\, F_0\right]^{1/5} t^{6/5}, \qquad c = (\varkappa p v)^{1/2} \qquad (1.5)$$

Maximum temperature is apparently achieved in the center of the layer, i.e. at the point $\frac{1}{2}m^\circ$ and is determined from Equation

$$e_{\max} = \left(\frac{3 a m^\circ F_0}{\varkappa^{1/2} 2(\varkappa - 1)^{1/2}}\right)^{1/3} \qquad (1.6)$$

Corresponding numerical calculations, for which results are presented in Fig.1 and 2, show that (1.6) is somewhat low value because the gas continues to heat up during some interval of time after the arrival of the rarefaction wave at the point $m = \frac{1}{2}m^\circ$

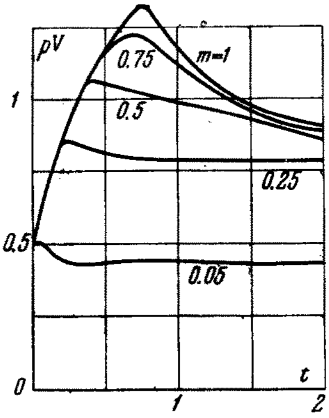

Fig. 1

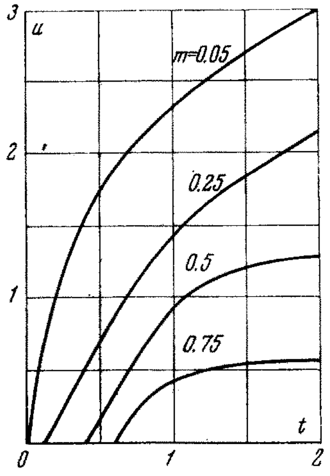

Fig. 2

In Fig.1 the change of dimensionless product pv is shown as a function of dimensionless time t (for relationships between dimensionless and dimensional variables see below) for various points of dimensionless mass.

In Fig. 2 the change of dimensionless velocity u is shown as a function of time for the same particles of material. An analogous picture occurs, as is shown by calculations, also in the case of spherical and cylindrical symmetry.

In the case when the gas fills the halfspace $m > 0$, a wave of heating propagates through this halfspace with a layer depth which is proportional to the length of passage of the radiation quantum $l = k^{-1} \sim e^{3/2} \sim t^{3/5}$ (see (1.4)). The rarefaction wave propagates according to the relationship $x \sim t^{6/5}$ (see (1.5)). Consequently, in the beginning of the process the width of the heating zone is significantly greater than the width of the region where the gas moves and therefore it is permissible to neglect the change in density. The problem of nonstationary heating wave with changing coefficient of absorption is self-similar and was examined in [4]. The heating wave has a sharp front similar to a heat wave in case of nonlinear heat conductivity. The character of temperature dependence in it is close to a plateau.

After some interval of time t_1, the rarefaction wave catches up with the heating wave. This time is determined by the relationship

$$l\ (t_1) = \int_0^{t_1} c(t)\, dt$$

where l is the average length of travel of the quantum over the heated region (equal to the depth of the heating zone), c is the sound speed. From this it is possible to determine the internal energy of gas e and the temperature at the front of the heating wave, which is achieved at the moment of arrival of the wave of rarefaction: $e\,(t_1) \approx (F_0 v_0)^{2/3}$.

In contrast to transparent mass in case of which the temperature has a maximum at the moment when the gasdynamic motion starts, it is not obvious for the case of heating of an unlimited mass of gas that a temperature decrease must take place with the beginning of gasdynamic motion.

In this case for $t \gg t_1$ a regime occurs for which the rarefaction wave front coincides with the heating wave front. For the absorption coefficient assumed above, the behavior mentioned turns out to be self-consistent [3]. The temperature increase takes place at the expense of absorption of incident flux in the region which is encompassed by the gasdynamic motion with specific volume $v_\varepsilon \gg v_0$. The optical thickness of this region turns out to be of the order of unity.

In connection with the possibility of existence of the mentioned behavior of heating of gas which fills the halfspace $x \geq 0$, the circumstance is assumed to be essential that the analogous self-consistent behavior can at least asymptotically stabilize itself in the interaction of strong laser radiation with material evaporated from the surface of the solid body. Indeed, the flux of laser radiation F_0 falling on the surface of a solid body is absorbed in a layer the thickness of which is of the order of 10^{-4} to 10^{-5} cm (strongly absorbing materials similar to metals are examined). After the time

$$t \gg \frac{c\sigma\omega^2}{k^2 F_0^2}$$

where c is the heat capacity, σ is the coefficient of thermal conductivity, ω is the energy of evaporation per atom, k is the Boltzmann constant, the internal energy e of the absorbing layer becomes much greater than the specific heat of vaporization and the vaporized material can be assumed to be a gas. Subsequent heating of vaporized material must take place in a self-consistent manner according to the following considerations.

Let the coefficient of absorption as before decrease with increase in temperature and increase with increase in density. We shall assume, for example, that the material evaporated up to some instant of time is transparent to incident radiation (low density and high temperature), then the vapors will only slightly screen the surface from which intensive evaporation of new portions of material will take place leading to an increase in density. This in turn increases the absorption of radiation in vapors and consequently the screening of the surface. The rate of evaporation decreases in the following moments, which now leads to a decrease in the coefficient of absorption, etc. The considerations presented indicate that the process under examination will lead to the situation where the optical thickness of the vaporized layer will reach some constant value.

The problem consists of finding a solution of the system of equations (1.1) for which the optical thickness of the layer of evaporated material will reach some constant value. Such a solution exists and is independent of the heat of sublimation. This naturally indicates that the self-consistent behavior is stabilized starting from the instant of time when the temperature of vapors at the surface of the solid body is much greater than $T = \omega/k$.

The existence of such a solution is formally related to the fact that in satisfying the indicated conditions the problem becomes self-similar. In fact, if the absorption coefficient of vaporized material has the form $K\ (\rho, T) = a_1 \rho^\alpha T^\beta = a_2 \rho^r p^s\ (r > 0,\ s < 0)$, then from the four determining parameters of the problem F_0, a, ρ_0 and ω, only the first two are essential (here we shall use Euler's coordinates x, t).

From dimensional considerations it follows in this case that the unknown functions u, ρ and p must have the form

$$u = \frac{1}{\theta} t^{-(\nu+1)} U(\lambda), \qquad \rho = F_0 \theta^3 t^{3(\nu+1)} R(\lambda), \qquad p = F_0 \theta t^{\nu+1} P(\lambda) \qquad (1.7)$$

$$\theta = [a_2 F_0^{r+s}]^{1/[1-(3r+s)]}, \qquad \nu = (3r+s)/(1-(3r+s))$$

Here $\lambda = \theta x t^{\nu}$ is the self-similar variable, $U(\lambda)$, $R(\lambda)$ and $P(\lambda)$ are dimensionless velocity, density and pressure, respectively.

Approximate solution of the corresponding system of self-similar equations for the case of plasma ($r = {}^7/_2$, $s = -{}^3/_2$) gives for temperature and density near the surface of the solid body and the amount of vaporized material the following expressions:

$$T = \frac{0.97}{R_0} \mu F_0^{1/2} a_2^{1/4} t^{1/4}, \qquad \rho = 0.31 F_0^{1/4} a_2^{-3/8} t^{-3/8}, \qquad m_u = 0.37 F_0^{1/2} a_2^{-1/4} t^{3/4} \quad (1.8)$$

Here R_0 is the gas constant, μ is the atomic weight. In this case the ratio of flux F incident on the surface of the solid body to the total flux F_0 has the value ≈ 0.78. The ratio of velocity u_1 of gas boundary with vacuum, and the velocity u_0 near the surface of the solid body is ≈ 5.2.

Let us continue the examination of gas heating for the case where the absorption coefficient changes in an exponential fashion. We note that gas-dynamic motion starts not only from the vacuum side but also as a result of pressure drop at the front of the heating wave. After the zone of sharp pressure gradients and large accelerations passes through a given particle, the velocity achieved will have the order of magnitude

$$u_0 \approx \frac{p}{\rho_0} \frac{\Delta t}{\Delta x} = \frac{p}{\rho_0 D} = \frac{c^2}{\varkappa D} \qquad (1.9)$$

Here Δx is the width of the "front" of the wave, p is the pressure in the heated region, Δt is the time of passage of the wave front through a given point, D is the velocity of motion of the wave front of heating. When D becomes smaller than the speed of sound in the heated medium, hydrodynamic perturbations separate from the front of heating wave and form a shock wave front. The pressure in the region of the self-consistent rarefaction wave changes according to the relationship $p \sim F_0^{3/4} t^{-1/8} a^{-1/8}$. If we consider that this region serves as a piston for the shock wave located at point m_b and the pressure on its front is equal to $p_* \sim p$, then

$$\frac{dm_b}{dt} \sim \sqrt{p v_0} = F_0^{3/8} v_0^{1/2} t^{-1/16} a^{-1/16}$$

and, consequently

$$m_b \sim F_0^{3/8} v_0^{1/2} t^{15/16} a^{-1/16} \qquad (1.10)$$

From this it follows that with passage of time the shock wave separates quite slowly from the zone of self-consistent rarefaction wave ($m_b \sim t^{15/16}$, while $m_u \sim t^{12/16}$).

Concepts presented above were checked by means of numerical calculations for the case where the heated substance is a gas with the equation of state $e = pv/(\varkappa - 1)$.

2. Now let us transform the system of equations (1.1) to a dimensionless form, introducing such factors u_0, p_0, t_0, m_0, v_0 and F_0 that on multiplying the corresponding variables u, p, t, m, v and F by these factors, Equations (1.1) do not change their form. For this the fulfilment of four relationships is required

$$u_0 m_0 = p_0 t_0, \quad v_0 m_0 = u_0 t_0, \quad p_0 v_0 m_0 = F_0 t_0, \quad F_0 = p_0^{-3/2} v_0^{5/2} F_0 a m_0 \qquad (2.1)$$

which we shall regard as a system of four equations with respect to four unknowns u_0, p_0, t_0 and m_0 , assuming the value v_0 to be equal to the initial value of the specific volume of gas, while F_0 is equal to the value of energy flux from the vacuum side. Then by the method of successive elimination of unknowns from (2.1), we find the relationships which we need

$$u_0 = (v_0 F_0)^{1/3}, \quad p_0 = v_0^{-1/3} F_0^{2/3}, \quad t_0 = \frac{1}{a} v_0^{8/3} F_0^{2/3}, \quad m_0 = \frac{1}{a} F_0 v_0^2 \qquad (2.2)$$

Now it is sufficient to solve system (1.1) for single values of initial specific volume of gas and external flow. For any other values the solutions are obtained by the method of multilpying the obtained functions by factors (2.2). In this connection it is necessary to take into account that the mass of the layer must be either unlimited or the recalculation will give a solution for a new mass of layer $m = m_1 F_0 v_0^2$, where m_1 is the mass of the layer for the solution with single parameters $(m_1 = 1/a)$.

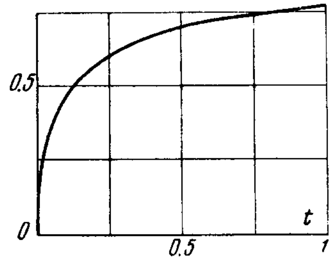

Fig. 3

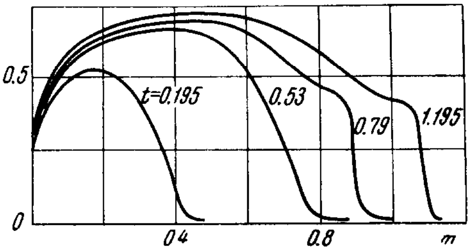

Fig. 4

For the case of constant radiation flux F_0 over the entire gas layer the last limitation is removed since the number of equations is less by one. In this case the transformation factors have the form

$$u_0 = (aF_0)^{1/6}, \qquad p_0 = \frac{(aF_0 m^\circ)^{1/3}}{v_0}, \qquad t_0 = \frac{m^{\circ 5/6} v_0}{(aF_0)^{1/6}} \qquad (2.3)$$

where the energy flux from vacuum is taken as F_0, v_0 is the initial specific volume of gas, m° is the mass of the gas layer. A system of ordinary differential equations was constructed which approximate the system of equations (1.1) with accuracy to quantities of the order of $1/n^2$

$$\frac{du_i}{dt} = -\frac{p_{i+1} - p_{i-1}}{2\Delta m}, \qquad \frac{dv_i}{dt} = \frac{u_{i+1} - u_{i-1}}{2\Delta m} \qquad \left(m = \frac{i}{n} m_1\right)$$

$$\frac{dE_i}{dt} = \frac{-(pu)_{i+1} + (pu)_{i-1}}{2\Delta m} + F_i e_i^{-\alpha} v_i^{-\beta} \tag{2.4}$$

$$e_i = E_i - \frac{u_i^2}{2}, \quad p_i = \frac{e_i(\varkappa - 1)}{v_i}, \quad F_i = \exp\left\{-\frac{\Delta m}{2} \sum_{j=1} (e_j^{-\alpha} v_j^{-\beta} + e_{j-1}^{-\alpha} v_{j-1}^{-\beta})\right\}$$

Here E_i is the total energy of unit mass of gas; the index i designates values of variables for m corresponding to $i = 0, 1, 2, \ldots, n$.

Initial values and boundary values for unknown functions entering into system (2.4) where taken in correspondence with initial values and boundary values of the original system (1.1) of partial differential equations.

System (2.4) is obtained under the assumption of sufficient smoothness of functions entering into the system. It is natural that in the region of the front of the shock wave where the values of derivatives are large, the computations will be made with considerable error, However the shock wave in the present problem does not appear at once and is not determining for the basic quantity sought which is the maximum temperature of the gas. Therefore system (2.4) was utilized for making the continuous calculation. With the purpose of eliminating the "bump" and large error near the front of the shock wave after its formation, an averaging technique was applied as a method of artificial smoothing of values according to a recommendation by A.A. Miliutin. The error of equations (2.4) increases in proportion to the increase of the difference

$$f_i - \langle f_i \rangle,$$

where

$$\langle f_i \rangle = {}^1/_3\, (f_{i+1} + f_i + f_{i-1}),$$

Therefore the following was adapted as a criterion for introduction of smoothing

$$\xi = 1 - \langle f_i \rangle / f_i$$

The value of f_i after averaging is taken to be equal to the arithmetic average of its values at points $i-1$, i and $i+1$, i.e. to the value $\langle f_i \rangle$ before averaging.

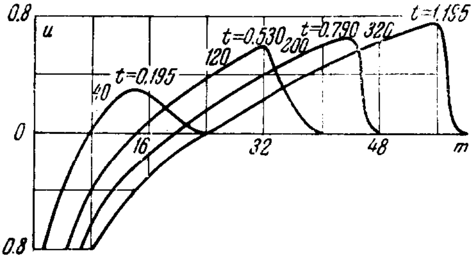

Fig. 5

In order to avoid averaging in the region of the leading front of the heating wave where sharp gradients of temperature occur until processes of hydrodynamic motion become substantial, the velocity was selected as the quantity from which the need for smoothing was determined.

Results of numerical computations presented in Fig. 3 to 5, are in satisfactory agreement with qualitative considerations presented above and with self-similar solutions (1.8).

In Fig.3 the change of the maximum value of dimensionless internal energy is shown as a function of dimensionless time. It is easy to see that for $t \approx 1$ sharp deceleration in growth of $e = pv/(\varkappa - 1)$ starts.

In Fig.4 the change of e is shown as a function of the dimensionless Lagrange's coordinate m for several times. The formation of a shock wave is clearly evident.

In Fig.5 the distribution of dimensionless velocity u as a function of dimensionless Lagrange's coordinate is shown for several instants of t . From a comparison of Figs. 4 and 5 it follows that starting with instants $t \approx 1$ the front of the rarefaction waves moves together with the front of heating, i.e. the self-consistent behavior has arrived.

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