GASDYNAMICAL MODEL OF THE VAPORIZING INTERACTION OF RADIATION WITH A LIQUID

A. F. Vitshas and Yu. I. Sentsov

UDC 532.529.5/6

For large radiation densities, when the thermal model of surface vaporization becomes inapplicable, the vaporization and motion of the resulting vapor can be treated in the framework of a gasdynamical description of the flow [1]. For liquid metals the limit of applicability of the thermal model corresponds to intensities of $I = 10^8$-10^9 W/cm^2 [2], while for a dielectric liquid it is about five or six orders of magnitude smaller because of the onset of fluctuational vaporization of the liquid [3].

The gasdynamical treatment of the vaporizing interaction between light and matter is based on the solution of gasdynamical equations in which the phase transition is taken into account either by replacing the equation of state of the liquid by that of the vapor when the phase transition takes place without an interface [4], or in the opposite case by introducing a strong gasdynamical rupture, which replaces the phase transition region [1]. The first approach (unlike the second) is appropriate for high laser intensities, for which the phase trajectory of the medium passes above the phase equilibrium curve.

The gasdynamical rupture was used in [5] to consider the interaction of radiation (λ = 10.6 μm) with water and the flow of the resulting vapor in an atmosphere of surrounding air. The Jouget condition was used, which assumes that the velocity of the escaping vapor is equal to the local speed of sound. In the general case of variable intensity or high back-pressure this assumption is incorrect.

In the present paper we use the numerical method of Godunov (involving moving grids [6]) to solve the problem of the vaporization of water and the motion of the resulting vapor into the surrounding air atmosphere for the case when the incident intensity is time dependent. Unlike the treatment of [5], here we use a model based on the nonadiabatic, radiation-induced destruction of the liquid–vapor interface to obtain general relations for the gasdynamical parameters of the vapor above the liquid surface. These parameters then give the boundary conditions for the flow of the vapor into the atmosphere of surrounding air.

Formulation of the Problem and Method of Solution. A one-dimensional picture of the gasdynamical motion of matter when the surface of a liquid is exposed to intense radiation is shown in Fig. 1. The layer of vapor formed as a result of the interaction expands because of the pressure drop and pushes against a layer of air, which is separated from the vapor by the surface 3, and from the unperturbed atmosphere by a shock wave 4. Because of the reaction of the vapor, a force acts on the surface of the liquid 2, which excites acoustic waves 1 in the liquid.

The propagation of laser radiation in an absorbing medium is described by Bouguer's law

$$\partial I/\partial x = kI, \tag{1}$$

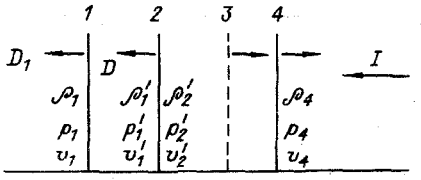

Fig. 1

Moscow. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 36-42, September-October, 1987. Original article submitted February 6, 1986.

0021-8944/87/2805-0675$12.50

where the absorption index k is zero for air, while in the vapors of liquids it is given by the expression $k = k_0(\rho/\rho_0)^2$ from [4]; $k_0 = 830$ cm^{-1}, $\rho_0 = 1$ g/cm^3 are the absorption coefficient and density of water. The air and water vapor were both assumed to be ideal gases with corresponding adiabatic indices of $\varkappa_a = 1.4$ and $\varkappa_v = 1.3$.

The method of [6] was used to specify the boundary conditions on the moving surfaces of the computational region. These boundaries coincide with the air–vapor interface and the shock wave. The boundary conditions for the vapor on the vapor–liquid interface were found, assuming that the destruction of the liquid–vapor interface under the action of the radiation is a nonadiabatic process.

Nonadiabatic Destruction of the Liquid–Vapor Interface. We model the phase transition region as a strong gasdynamical rupture, and in the notation of Fig. 1 we write down the integral identities following from the conservation laws of mass, momentum, and energy for a contour enclosing the rupture [6]:

$$\begin{aligned}
&(\rho_1' - \rho_2')\,D = \rho_1'v_1' - \rho_2'v_2',\\
&(\rho_1'v_1' - \rho_2'v_2')\,D = p_1' + \rho_1'v_1'^2 - p_2' - \rho_2'v_2'^2,\\
&\left[\rho_1'\left(\varepsilon_1' + \frac{v_1'^2}{2}\right) - \rho_2'\left(\varepsilon_2' + \frac{v_2'^2}{2}\right)\right]D = \rho_1'v_1'\left(\varepsilon_1' + \frac{v_1'^2}{2}\right) - \rho_2'v_2'\left(\varepsilon_2' + \frac{v_2'^2}{2}\right) + p_1'v_1' - p_2'v_2' + I.
\end{aligned} \tag{2}$$

Here ρ is the density; p, pressure; ε, internal energy per unit mass of gas; v, velocity; I, intensity of the radiation. Linearization of (2) in the small parameters ρ_2'/ρ_1', v_1'/c, $\varepsilon_1'/\varepsilon_2'$ gives a simpler set of relations:

$$\begin{aligned}
&\rho_1'(D - v_1') = \rho_2'v_2', \quad p_1' = p_2' + \rho_2'v_2'^2,\\
&\rho_2'v_2'(\varepsilon_2' + v_2'^2/2 + p_2'/\rho_2') = I, \quad v_1' = p_1'/\rho_1'c.
\end{aligned} \tag{3}$$

An important conclusion following from (3) is that the velocity of motion D of the phase transition boundary can be neglected in comparison with the velocity of motion of the vapor v_2'. In this case, most of the energy is carried off by the vaporized material, and the liquid obtains a reactive momentum equal to the momentum of the escaping vapor. Hence, the vaporization process can be treated assuming an unperturbed liquid. Then, using the calculated reactive pressure, one can compute the excitation of sound in the liquid [7]. The system of equations (3) contains five unknowns, of which two can be determined by considering the vaporization mechanism of the liquid and the flow pattern of the vapor.

When a dielectric liquid is exposed to intense radiation, boiling of the liquid throughout the volume of the liquid results. The liquid transforms into a metastable state, and because of fluctuational nucleation, vapor bubbles grow rapidly [8]. The rate of nucleation increases exponentially as the liquid approaches the stability boundary, which is determined by the spinodal curve. For the case of water considered here, the spinodal curve relating the pressure and temperature of the boiling liquid has the form [9]

$$T = T_*(0.9 + 0.1p/p_*), \tag{4}$$

where $T_* = 647$ K and $p_* = 221 \cdot 10^5$ Pa are the critical temperature and pressure. An analysis of the kinetics of volume boiling shows that the time required to establish quasisteady vaporization in the phase transition layer does not exceed several nanoseconds [9]. This value of the time is taken as the limit of applicability of the strong rupture model for the volume mechanism of the boiling of the liquid.

When the pressure of the liquid is above the critical pressure, Eq. (4) is inapplicable since the transition of liquid into vapor occurs without any sudden change of state and the difference between the two phases is nominal. Here it is necessary to solve a purely hydrodynamical problem for a continuous state of the medium [4]. However, according to [1], the rupture model can be extended to supercritical pressures. Let ρ^* be the density for which the vapor is transparent to radiation, which therefore defines the right boundary of the rupture in the vapor region. The value of ρ^* is given by the condition that the liquid has reached the critical pressure

$$\rho^* = p_*/(\varkappa + 1)\,RT_*. \tag{5}$$

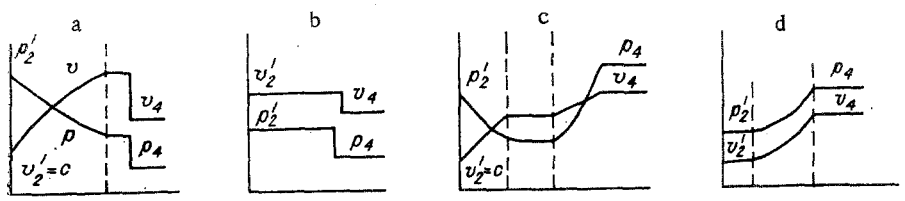

Fig. 2

This definition of the maximum vapor density on the outer boundary of the rupture is questionable, but it is shown in (7) that the dependence of the pressure on this quantity is weak, going as the cube root.

If we assume that the vapor has the temperature of the boiling liquid, then (4) is an additional relation between the vapor temperature T_2' and the pressure of the liquid p_1'. In the opposite case, (5) gives the additional relation.

The last missing relation is found by considering the flow pattern of the vapor onto the adjoining layer of gas. The gasdynamical solution for the flow of the vapor will be sought within the class of possible self-modeling solutions for the adiabatic destruction of an arbitrary rupture [10].

Let the parameters of the gas bounding the liquid have the values p_4, ρ_4, v_4. If v_2' and p_2' of the inflowing vapor satisfy the condition

$$v_2' - v_4 \leqslant (p_2' - p_4)\Big/\left[\rho_4\left(\frac{\varkappa+1}{2}p_2' + \frac{\varkappa-1}{2}p_4\right)\right]^{1/2}, \tag{6}$$

then flow accompanied by propagation of rarefaction waves toward the surface of the liquid and against the flow is possible. Steady-state values of the gasdynamical parameters on the boundary can result only when the velocity of the incoming vapor is equal to the local speed of sound. In this case, as in [1], we have a self-modeling flow pattern (Fig. 2a). The simultaneous solution of the system of equations (3) with the additional relation (4) or (5) and the condition that the velocity of the incoming vapor be equal to the local speed of sound gives the following analytical expression for the boundary values of the parameters of the inflowing vapor:

$$p_2' = I\Big/\left[(\varkappa RT_*)^{1/2}\left(\frac{\varkappa(\varkappa+1)}{2(\varkappa-1)} + \frac{L}{RT_*}\right)\right], \tag{7}$$

$$T_2' = T_*(0{,}9 + 0{,}1p_1'p_*), \quad v_2' = (\varkappa RT_2')^{1/2}, \quad p_1' = (\varkappa+1)p_2' \text{ for } p_1' \leqslant p_*;$$

$$p_2' = I^{2/3}\rho^{*1/3}\Big/\left[\varkappa\left(\frac{\varkappa+1}{2(\varkappa-1)} + L\rho^*/\varkappa p_2'\right)^{2/3}\right], \quad \rho_2' = \rho^*,$$

$$v_2' = (\varkappa RT_2')^{1/2}, \; p_1' = (\varkappa+1)p_2' \text{ for } p_1' > p_*.$$

Here $\varkappa$ is the adiabatic index of the liquid vapor; L, latent heat of vaporization; R, specific gas constant for the vapor. As one approaches the critical point, the properties of the liquid and vapor vary sharply; for example, the latent heat of vaporization goes to zero. It would be difficult to take into account the variation of these properties analytically and, therefore, in the framework of the ideal gas model, the adiabatic index and latent heat of vaporization are assumed to be constants. In addition, for supercritical pressures, where the latent heat of vaporization should be rigorously zero, we assume it remains equal to the value in the subcritical region in order to obtain a smooth dependence of the reaction pressure on the radiation intensity at the critical point. For large pressures this error goes away, since the term containing the latent heat of vaporization in (5) goes to zero.

If the parameters of the inflowing vapor found in (7) do not satisfy condition (6), then the inflowing vapor cannot have the speed of sound because a shock wave must propagate toward the surface of the liquid, which destroys the sonic flow regime. In this case the solution is found as follows. If the pressure found formally from (7) satisfies $p_2' > p_4$ and the velocity v_2' does not satisfy condition (6), then the solution corresponding to steady-state boundary conditions is found for the flow pattern in Fig. 2b, which corresponds to a uniform gas flow with parameters p_2', v_2', T_2' related adiabatically to the parameters of the external medium p_4, v_4, T_4. The boundary parameters of the inflowing vapor are found from the simultaneous solution of the following system of transcendental algebraic equations:

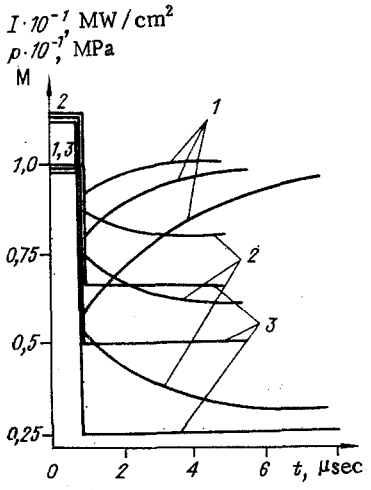

Fig. 3

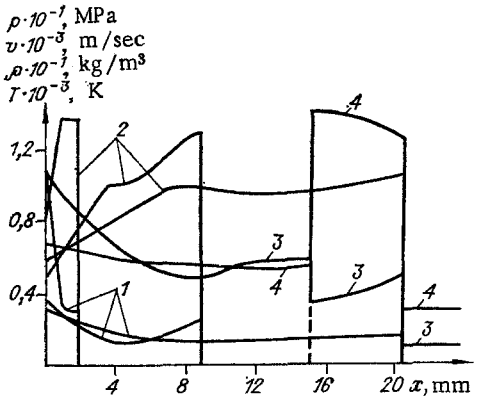

Fig. 4

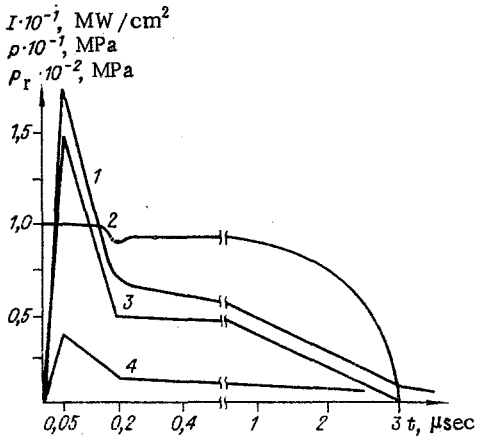

Fig. 5

$$\rho_2' v_2' \left[\varkappa p_2'/\rho_2' (\varkappa - 1) + v_2'^2 + L\right] = I, \tag{8}$$
$$v_2' = v_4 + (p_2' - p_4)\left/\left[\rho_4\left(\frac{\varkappa+1}{2} p_2' + \frac{\varkappa-1}{2} p_4\right)\right]^{1/2}\right.,$$
$$p_1' = p_2' + \rho_2' v_2'^2, \quad p_2' = \rho_2' R T_2',$$
$$T_2' = T_* (0.9 + 0.1 p_1'/p_*) \; (p_1' \leqslant p_*), \quad \rho_2' = \rho^* \; (p_1' > p_*).$$

If the parameters of the inflowing vapor obtained formally in (7) satisfy the condition

$$v_2' \leqslant v_4 - [2/(\varkappa - 1)] (\varkappa p_4/R)^{1/2} [1 - (p_2'/p_4)^{(\varkappa-1)/2\varkappa}] \tag{9}$$

and $p_2' < p_4$, then we have the flow pattern of Fig. 2c with two rarefaction waves propagating against the flow and along the flow. In this case the boundary parameters are given by (7). If the pressure obtained formally from (7) satisfies $p_2' < p_4$, while the velocity v_2' does not satisfy condition (9), then depending on the direction of the inequality $\rho_4 v_4 (\chi p_4/(\chi - 1)\rho_4 + v_4^2/2 + L) \gtrless I$ the flow has the form shown in Fig. 2b (for $\leqslant$) or Fig. 2d (for $>$). The values of the boundary parameters for Fig. 2b are given by (8). The flow pattern of Fig. 2d corresponds to propagation of rarefaction waves downward along the flow and the values of the boundary parameters are found from the condition that the velocity of motion of the gas on the left boundary be equal to the velocity of the rarefaction wave

$$\rho_2' v_2' (\varkappa p_2'/(\varkappa - 1)\rho_2' + v_2'^2/2 + L) = I, \tag{10}$$
$$v_2' = v_4 - [2/(\varkappa - 1)] (\varkappa p_4/R)^{1/2} [1 - (p_2'/p_4)^{(\varkappa-1)/2\varkappa}],$$
$$p_1' = p_2' + \rho_2' v_2'^2, \quad p_2' = \rho_2' R T_2',$$
$$T_2' = T_* (0.9 + 0.1 p_1'/p_*) \quad (p_1' \leqslant p_*),$$
$$\rho_2' = \rho^* \quad (p_1' > p_*).$$

The solutions (7), (8), and (10) exhaust the possible gasdynamical flow regimes induced by laser irradiation of the surface of a liquid dielectric.

The destruction of the rupture was considered at each time step for values of the radiation intensity at the surface and parameters of the external gas taken in the boundary cell of the grid at the preceding time step. The absorption of radiation in the water vapor was taken into account by adding a bulk heat production term kI to the energy balance difference equation. In this case a "large number" was defined by considering the destruction of an arbitrary rupture, as in the case of adiabatic flow [6].

Results of the Calculations. Numerical results were obtained for two forms of the dependence of the radiation intensity on time. The first case was a step-function intensity and involved a study of the transient process of establishing the flow. The second example was the experimentally observed shape of the radiation in pulse CO_2 lasers. Figure 3 shows the results for the computed time-dependence of the static pressure and Mach number on the liquid boundary for a step-function radiation intensity (curves 1-3 correspond to the Mach number, pressure, and intensity of the radiation, respectively). The time to establish the new self-modeling flow is determined in general by the duration of the preradiation and by the magnitude of the jump in the intensity. The calculations were done neglecting absorption by the water vapor. It is evident from Fig. 3 that when the duration of preradiation is 1 μsec, the duration of the transient is approximately proportional to the magnitude of the jump in the intensity (2-10 μsec). In [11] thermal surface vaporization of a liquid metal was considered and the time to establish the flow depended on the characteristic heat conduction and gasdynamical flow times. In contrast, in our case it is determined solely by the gasdynamics and does not involve the characteristic time to establish bulk fluctuational vaporization. This time is about $\lesssim 10^{-9}$ sec, and it was set equal to zero in the calculations.

Figure 4 shows the response of the gasdynamical parameters of the medium at different times to a jump in the intensity (1:0.25). Curves 1 and 2 shows the pressure and velocity profiles at t = 1, 5, 13 μsec, and curves 3 and 4 show the density and temperature at t = 13 μsec. It is evident that the time required to establish the new self-modeling flow is determined by the resorption time of the "wake" from the initial intensity of the radiation.

The calculated results for the model dependence of the laser radiation are shown in Fig. 5, where curves 1-4 show the dependence of the static pressure, Mach number, intensity of the radiation, and reaction pressure p_r on time. It is evident from the results that the escape velocity of the vapor for the duration of the radiation spike remains sonic, except for the front edge of the spike, which is not resolvable in the figure, and the tail end of the spike, where the velocity dips. The velocity then increases, approaching the sonic value and toward the end of the pulse it falls rapidly.

Comparison of the p_r calculated on the surface of the liquid with the pressure calculated assuming that vapor escapes with the speed of sound shows close agreement up to the end of the laser pulse. The difference at t = 2 μsec is 4%, and at t = 2.5 μsec it is 10%. However, in many practical cases these differences can be neglected and then the reaction impulse can be found by using analytical expressions for the sonic emission regime as given by (7).

The calculations for a special form of the radiation and for a model absorption coefficient show that the effect on the flow pattern of absorption of the radiation by water vapor is insignificant. The difference in the results does not exceed 10%. In the case of a liquid with strongly absorbing vapor (this can also occur for the plasma interaction regime of radiation with water) the approximation of emission at the speed of sound becomes inapplicable, and then the calculations must be done according to the model discussed here.

Finally, we note that the approximate expression for the reaction pressure p (Pa) = 2.6 I (W/cm^2) obtained from (7) is in good agreement with the experimental results [3].

LITERATURE CITED

1. Yu. V. Afanas'ev and O. N. Krokhin, "Gasdynamical theory of the effect of laser radiation on condensed matter," Kvantovaya Radiofiz., Tr. FIAN, 52 (1970).
2. S. I. Anisimov, A. Ya. Imas, G. S. Romanov, and Yu. V. Khodyko, Effect of Intense Radiation in Metals [in Russian], Nauka, Moscow (1970).

3. A. F. Vitshas, V. V. Grigor'ev, et al., "Excitation of a pressure pulse in water in the explosive vaporization of the surface layer," Pis'ma Zh. Tekh. Fiz., 9, No. 23 (1983).
4. F. D. Feiock and L. K. Goodwin, "Calculation of laser-induced stresses in water," J. Appl. Phys., 43, No. 12 (1972).
5. A. F. Vitshas, V. V. Korneev, et al., "Study of shock waves in air induced by the vaporizing interaction of radiation on the surface of a liquid," Zh. Tekh. Fiz., 55, No. 4 (1985).
6. S. K. Godunov, A. V. Zabrodin, et al., Numerical Solution of Multidimensional Problems in Gasdynamics [in Russian], Nauka, Moscow (1976).
7. A. F. Vitshas, V. V. Grigor'ev, et al., "Generation and propagation of sound in the vaporizing regime of the interaction of radiation with water," Akust. Zh., 31, No. 3 (1985).
8. V. N. Kondrat'ev, "On the vaporization mechanism induced by the interaction of intense energy sources with matter," Zh. Prikl. Mekh. Tekh. Fiz., No. 5 (1972).
9. V. P. Skripov, E. N. Sinitsyn, et al., Handbook of Thermophysical Properties of Liquids in the Metastable State [in Russian], Atomizdat, Moscow (1980).
10. L. D. Landau and E. M. Lifshits, Mechanics of Continuous Media [in Russian], Gostekhizdat, Moscow (1953).
11. V. I. Mazhukin and A. A. Samokhin, "On some features of the mathematical model of intense surface vaporization of matter," Dokl. Akad. Nauk SSSR, 281, No. 4 (1985).

APPROXIMATE SCALING LAWS OF HOMOGENEOUS CONDENSATION IN EXPANDING SUPERSONIC GAS FLOWS

S. A. Palopezhentsev

UDC 533.011.8:536.423.4

Due to the extreme complexity of the process of nucleation and growth of condensed-phase particles, the problem of gas flow with condensation cannot be solved analytically even with simple unidimensional flow models. The author of [1] used the example of flows of a condensing gas in supersonic nozzles and analyzed the corresponding dimensionless equations to show that exact modeling is also impossible. At the same time, the existence of different empirically established correlations connected with condensation in supersonic flows suggests that it is possible to find approximate similarity. There has been a whole range of studies devoted to establishing approximate scaling laws for condensation in expanding supersonic gas flows. The difference in the approach to the solution of the given problem and in the formulations and the generality of the resulting laws make it incumbent to conduct a comparative analysis of these investigations.

The study [2] was the first investigation to sufficiently thoroughly establish the scaling conditions, using as an example the approximate solution of the problem of condensation in a cloud of a vaporized substance during spherical dispersion into a cavity. Condensation kinetics was described by using the classical Frenkel–Zeldovich formula for the rate of formation of critical nuclei as a function of the degree of supercooling ϑ: $I = c \exp(-b/\vartheta^2)$. Here, $\vartheta = (T_p - T)/T_p$ (T_p is the temperature of vapor saturated at the given density). The extremely heavy dependence of the rate of nuclei formation on the degree of supercooling leads to a situation whereby most of the condensation centers ν are formed on a very small section of the expansion stage corresponding to maximum supercooling ϑ_m:

$$\nu = \int_{t_s}^{\infty} I dt' \approx I(\vartheta_m)\,\Delta t_m$$

Novosibirsk. Translated from Zhurnal Prikladnoi Mekhaniki i Tekhnicheskoi Fiziki, No. 5, pp. 42-49, September-October, 1987. Original article submitted July 25, 1986.

 0021-8944/87/2805-0680$12.50