Gas dynamics of slow luminous burning of air in a neodymium laser beam

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An optical discharge has been obtained for the first time in the slow burning regime with a steady-state gas motion pattern. A model is proposed for describing the gas dynamics of the discharge propagation, in which the ratio of the observed velocity to the velocity of the discharge through a gas at rest is equal to the ratio of the sound velocities in the discharge and in the cold gas.

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The present experiments, as in the first paper on the slow burning of a laser plasma,[1] were performed in laboratory air. The optical discharge was ignited at the caustic of the lens ($f = 1$ m), focusing a spikeless radiation pulse of a millisecond neodymium laser (Fig. 1,a) into a 4.2-mm diameter spot1). Initiation was accomplished in the triggering plasma of an optical breakdown of air by the pulse of an auxiliary neodymium laser (2 J energy, 0.1 μsec length), the beam of which could be focused at different points of the caustic of the primary milli-second laser perpendicular to its axis. During its luminescence (60 μsec) the triggering plasma was "caught up" by the primary beam. This led to propagation of the discharge from the initiation point nearly symmetrically forward and backward along the beam. As a result a plasma column was formed that was optically thin at the laser radiation wavelength that extended to a length up to 18 cm during the time the radiation was acting and that had a cross section of 1–2 cm. The absorption coefficient α, at the frequency of the neodymium laser, measured from the transmission of the primary laser radiation averaged over the length of the plasma column, remained constant over an interval of 1.5–4 msec within the accuracy limits (20%) of the measurements. For a laser pulse $P = 1$ and 2 MW at the maximum we obtained $\omega = 0.03$ and 0.02 cm^{-1}, respectively.

The major results are shown in Fig. 1,b and Fig. 2. In the first milli-second of discharge burning, when its longitudinal dimension is not large $l \leqslant 2R$, we observe a rapid decrease with time of the velocity of the two outside fronts of the discharge (Fig. 1,b). At the start of this stage of burning, simultaneously with the formation of the outside fronts of the periphery of the initiating breakdown, a quenching of the plasma is observed at the point of initiation ~0.1 msec after ignition (Fig. 2). The resulting

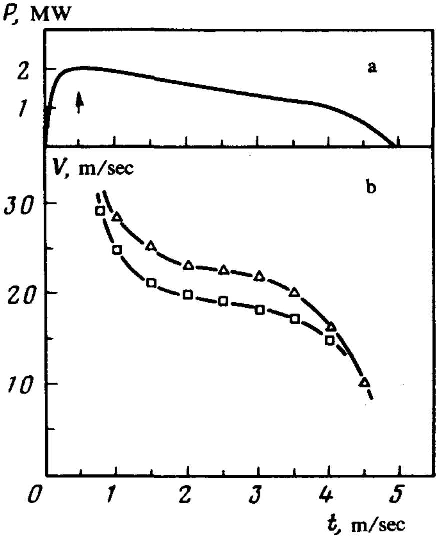

FIG. 1. Transient behavior of radiation power of primary laser (a) for 8.3 kJ energy in pulse (arrow indicates moment of discharge initiation) and the corresponding time dependence of the measured velocities of the leading (upper curve) and trailing fronts of the optical discharge (b).

gap of the plasma column closes ~1 msec after appearance at an average velocity of ~5 m/sec. The time required to reestablish ionization at the center of the discharge is shortened with an increase in the energy of the primary laser pulse. After this a stage is achieved of slow variation of the velocity $V(t)$ with time, over an interval of 2.5 msec,

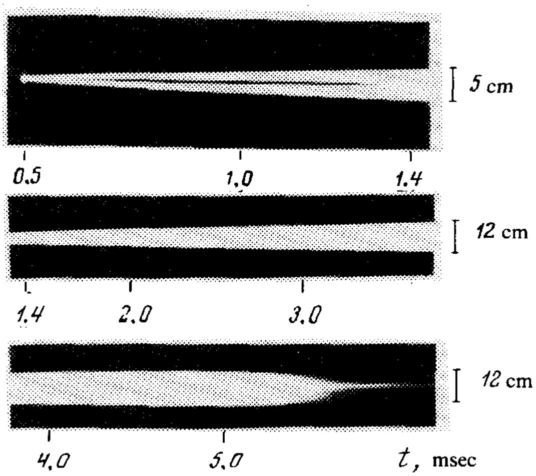

FIG. 2. Slit scan of optical discharge plasma glow. In the photographs the laser beam is directed from bottom to top. The time is measured from the start of laser pulse. The laser radiation energy in this experiment was 4 kJ (discharge was initiated at neck of caustic of $f = 1$ m lens).

in which the laser radiation power changes little. During this interval, the value of $V(t)$ is close to 20 m/sec (Fig. 1,b). The velocity values measured during this stage at points of the caustic with $R_1 = 0.42$ cm and $R_2 = 0.22$ cm are described by the empirical relations V_1 (m/sec) $= 11.5\ I^{1/2}$ for $I = 1$–3 MW/cm^2 and V_2 (m/sec) $= 7.9\ I^{1/2}$ for $I = 3$–10 MW/cm^2, respectively. At the end of the sweep in Fig. 2 we observe appreciable discharge plasma glow for ~ 1 msec after termination of the laser pulse.

The observed character of the time variation of the optical discharge propagation rate is explained by the movement of the gas in the discharge and ouside it (Fig. 3), arising because of the expansion of the gas, heated at the burning front. It follows from the conservation of matter flow at the burning front

$$\rho_0 u = \rho_k (v_k + V)$$

that in the initial stage of the discharge, when its length is small $l < R$ and the situation is similar to the propagation of burning from the closed end of a tube ($v_k = 0$) because of the gas-dynamic interaction of the fronts, the velocity $V \sim u\rho_0/\rho_k$. As the fronts move away from each other, the restrictions on the movement of the hot gas are reduced, a value $v_k > 0$ appears and the value of V decreases, approaching its value for the steady-state pattern of gas motion when $l \gg R$ and the influence of the fronts on each other can be ignored. In this case, the model of the motion of the burning front along an infinite tube (Fig. 3), one half of which is filled at time $t = 0$ with an at-rest hot gas while the other is filled with cold gas, can be used to calculate the value of V. Because of gas expansion at the front, compression waves, which are separated from the stationary gas by weak shock waves, start to propagate along the tube. By means of

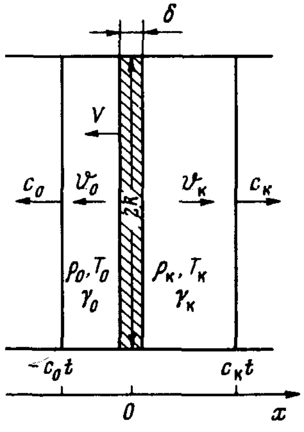

FIG. 3. One-dimensional model of gas-dynamic picture of discharge in laboratory coordinate system. The laser beam is directed along the X axis. The burning front of thickness $\delta < R$ at time $t = 0$ starts to move from the point $x = 0$ oppositely to the beam with velocity $V = u + v_0$; u is the velocity of the burning front with respect to the cold gas ahead of the front. v_0, ρ_0, T_0, γ_0, c_0 and v_k, ρ_k, T_k, γ_k, c_k are the gas velocity, density, temperature, adiabat exponent and velocity of sound in the gas in front of and behind the buring front, respectively.

the momentum conservation law (for $v_0 \ll c_0$, $v_k \ll c_k$)

$$\rho_0 v_0 c_0 t = \rho_k v_k c_k t$$

within an accuracy of small quantities $\sim (\rho_k/\rho_0)^{1/2}$ we obtain $(v_0/v_k) < 1$ and

$$V/u = c_k/c_0 = (\gamma_k \rho_0 / \gamma_0 \rho_k)^{1/2}. \tag{1}$$

The result (1) is considerably different from the relation $V/u = \rho_0/\rho_k$ for burning from the closed end of a tube, which was previously used in Refs. 1, 2. The difference of the real situation from the one-dimensional model leads to a reduction of V because of the lateral dispersion of the gas. The u value far from threshold is given by the approximate relation (see Ref. 2)

$$\rho_0 u = (\alpha I \kappa / c_p w)^{1/2}, \tag{2}$$

where α, κ, c_p, w are the absorption coefficient of the laser radiation, the thermal conductivity, the specific heat at constant pressure, and the enthalpy of air at an ionization temperature $T_m < T_k$.

An analysis (using the data of Refs. 3, 4) of the balance of energy release and loss in the discharge plasma[2], and calculations of V from Eqs. (1)-(2) (taking into account the contribution, assumed in Ref. 5, of the radiant heat conductivity of the hot air because of the UV spectrum of its natural radiation) give the following estimate of the basic quantities, characterizing the slow luminous burning of air for the conditions of our experiment at $I = 3$ MW/cm^2 ($R = 0.42$ cm): $T_m = (11.5\text{–}12.5)\times 10^3$ K, $T_k = (17\text{–}19)\times 10^3$ K, $u = (1.7\text{–}2.7)$ m/sec, $V = (27\text{–}40)$ m/sec. The calculated V value agrees satisfactorily with the burning front velocity of 20 m/sec, measured in ten experiment under these conditions.

[1)] The caustic length, determined by the relation $R \leqslant (\sqrt{2}) R_{\min}$ (R is the beam radius), was 13 cm. The deviation of the intensity from the average value in any cross section of caustic did not exceed 35%.

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