Hydrodynamic interaction of slow-burning laser discharges and its use to study the gas motion in a discharge

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A hydrodynamic interaction of two laser discharges in the beam from a neodymium laser has been observed. The experimental data prove that the gas is moving both ahead of and behind the discharge front under slow-burning conditions.

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The simultaneous slow burning of two laser discharges in a laser beam has been arranged for the first time, and a hydrodynamic interaction between these discharges has been observed.$^{1)}$ As the oppositely directed plasma fronts of the two discharges slow down, the cold gas ahead of a front is set in motion. This fact is crucial to the problem of constructing a physical model for the propagation of a discharge.

The output pulse from the neodymium laser used in the present experiments had a smooth profile, a length of 5 ms, and an energy $E \leqslant 8$ kJ (Ref. 1). The beam was focused into the air of the laboratory by a lens with $f = 1$ m. The spot diameter at the

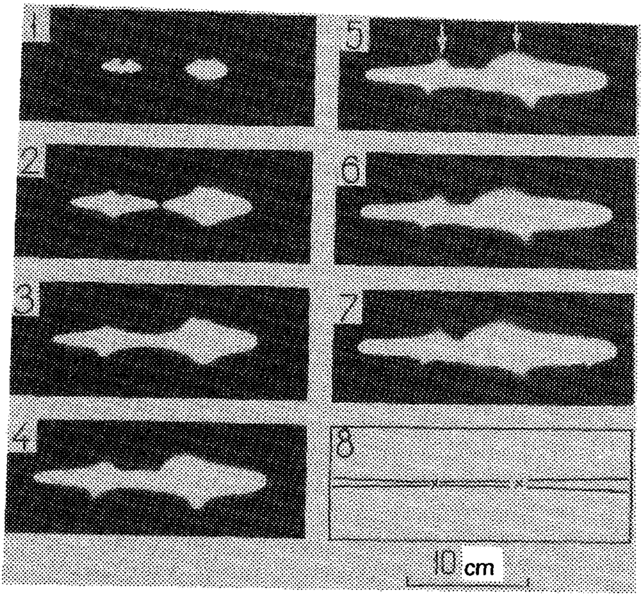

FIG. 1. Various stages in the evolution of a laser discharge when discharges are initiated at two points: at the caustic neck and 7 cm ahead of it. The laser beam is incident from right to left and has an energy $E = 4.9$ kJ. 1–$t = 0.5$ ms; 2–1.5; 3–2.0; 4–2.75; 5–3.25; 6–3.75; 7–4.25 ms; 8–diagram showing the laser beam and the initiation points (x).

neck of the caustic was 4 mm, and the length of the caustic at the half-intensity level was 14 cm. Since light with $\lambda = 1.06$ μm is absorbed only slightly in a plasma of atmospheric air, discharges can be initiated simultaneously at several points along the beam axis. In the present experiments, discharges were initiated at two points on the caustic. A nucleating plasma was produced through the breakdown of air by the beams from two auxiliary Q-switched lasers. After the initiation, we observed the

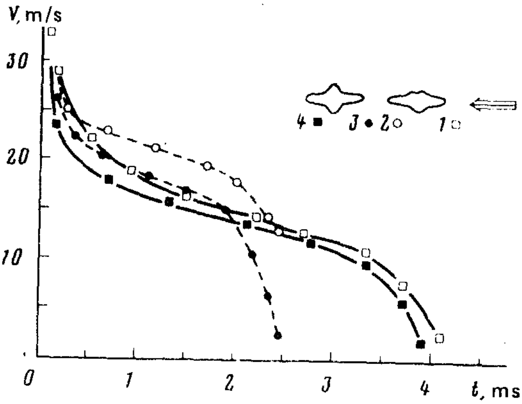

FIG. 2. Time evolution of the velocities of the discharge fronts for initiation at two points, ±5 cm from the caustic neck. The laser energy is $E = 4.3$ kJ. The inset at the upper right is a diagram of the discharge; the arrow shows the direction of the laser beam.

simultaneous motion of four laser-burning fronts (Fig. 1); the discharge propagated along and opposite the laser beam from each initiation point.

Figure 2 shows the time evolution of the front velocities for the case of discharge initiation at points positioned symmetrically with respect to the caustic neck. In the time interval $t = 0.8$-1.7 ms after the time of ignition, all the fronts are propagating at roughly constant velocities. As the discharges close on each other at $t \approx 1.7$ ms, however, we observe a sharp decrease in the velocities of the inner fronts. The distance between these fronts at this time is ~2.5 cm. At $t = 2.53$ ms, the volumes filled with glowing plasma merge. The observed decrease in the velocities of fronts 2 and 3 as they close on each other implies that the interaction between them is of a hydrodynamic nature, i.e., that there are flows of cold air away from the burning fronts. The extent to which the closing velocity of the inner fronts decrease, from $V_2 + V_3 = 35$ m/s (at $t = 1.7$ ms) to 15.5 m/s (at $t = 2.45$ ms), is evidence that the velocity of the cold gas ahead of the burning front is at least 10 m/s in the laboratory coordinate system.

Since there are flows of cold gas ahead of the burning fronts, and since the pressure in the discharge can be assumed uniform (because of the low observed velocities), we conclude from momentum conservation that there must be flows of a hot gas away from the fronts into the discharges. The observed shape of the glowing discharge region suggests something about the nature of the motion of the hot gas in the discharge (Fig. 1). The diameter of this region is much larger than that of the beam which sustains the discharge. The local nature of the swelling of the glowing plasma region (for example, the swelling in the regions marked with the arrows in frame 5 in Fig. 1) implies that these swelling regions are of a gas-dynamic origin: Near a swelling region of this type there is a flow of hot plasma away from the discharge axis. If the energy were transported out of the energy-evolution zone exclusively by heat conduction, we would observe a discharge with a "smooth" shape. The expanding and thus slowing flows of hot gas away from the front of each of the discharges (frame 2 in Fig. 1) collide in the central part of the discharge, giving rise to gas flows directed at an angle from the discharge axis. The details observed in the central parts of the discharges (frame 2) are attributed to these flows. The picture of the collision of the flows from the fronts corresponds in a qualitative way to the solution found for the problem of the collision of oppositely directed jets.[3]

New data on the gas motion in the discharge can be extracted by observing the change in the shape of the glowing region after the inner fronts merge (frames 4-7 in Fig. 1). This change in shape can be explained as a consequence of a change in the gas motion in the discharge. After the flows of hot gas from the inner fronts stop, we observe a penetration of jets from the outer fronts into the hot gas which has come to a halt between the two regions where the flows from the two discharges previously collided. The asymmetry of the motion with respect to the discharge axis which is observed here is not exceptional in such processes (see Ref. 4, for example). The jet penetration velocity, which can be identified in a first approximation as the velocity of the details on the upper edge of the discharge toward the center of the discharge, is ≈ 16 m/s for the flow from the leading discharge front (the front at the right in Fig. 1). The corresponding velocity observed for the left part of the discharge is considerably lower. In this case, because of the smaller initial diameter of the gas flow (the diameters of the burning fronts at the right and left differ by a factor of about two), we would apparently have to be more cautious about identifying the velocity at which the plasma jet penetrates into the immobile hot gas with the velocity of the details in the shape of the discharge. Working from the solution of the problem of the penetration of a jet into a liquid which is at rest,[5] and assuming that the densities are the same in the jet and in the gas at rest, we find that the flow velocity of the hot gas is twice the penetration velocity, having the value ≈ 30 m/s. We note that this is an estimate of the flow velocity of the hot gas far from the burning front; near the burning front, the velocity may be considerably higher.

In summary, these experiments have yielded proof that the gas both ahead of and behind the laser-discharge front is in motion under slow-burning conditions. The results found for the gas velocities are in accordance with the model proposed in Ref. 1 ("burning in an infinite tube") for calculating the velocity of the discharge front. Similar experiments on the interaction of strongly absorbing discharges propagating in two different beams from CO_2 lasers would be worthwhile. The discharge "collision" technique described here could also be used to study the physics of the propagation of laser discharges of other types, including supersonic discharges.

[1)] How an isolated discharge propagates and is sustained has been studied in several places (see Ref. 1 and the review paper of Raĭzer[2]).

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