Hypersonic gasdynamic studies in a gas flow arising from the application of an intense unfocused laser pulse to a film or to the surface of a bulk medium

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It is suggested that a fast pulsed gas flow with a velocity $\simeq 10^6$ cm/s can be produced by applying an intense unfocused laser pulse to the surface of a bulk medium or to a film which can evaporate. This possibility has been studied. The properties of this flow are described. Preliminary experiments on hypersonic flow around objects and on "cumulative" effects are described.

Hypersonic studies usually involve huge pulsed or cw gasdynamic tubes and nozzles (Ref. 1, for example). Producing high-velocity flows requires either high power levels to heat and accelerate the working gas or the use of helium. Plasma accelerators[2] are more suitable for simulating the interaction of the solar wind or pulsed high-velocity plasma flows[3] at velocities of 10^7–10^8 cm/s with bodies (planets, comets, etc.) in space. However, the high velocity, the nonequilibrium ionization, and the residual currents and fields associated with these accelerators (particularly in the case of an electric-discharge plasma or the plasma of the nonequilibrium dispersal caused by a focused laser beam) make these accelerators unsuitable for simulating aerospace processes with velocities $\simeq 10^6$ cm/s (for example, during flight or during the entry of space systems into an atmosphere).

In this letter we are reporting a study of the possibility of producing fast pulsed gas flows with easily adjustable parameters and properties by applying an intense unfocused laser pulse to the surface of a film or a bulk medium (graphite or aluminum) at optical power densities $(1\text{–}2)\times 10^8$ W/cm^2. A Q-switched neodymium laser based on a GOS-1001 laser was used (it had a passive Q switch with a bleachable LiF filter). It produced giant pulses with an energy of 40–50 J and a length of 30 ns. The diameter of the laser beam at its target (after compression by a telescope system) was 3.5 cm. The transverse distribution of light intensity was smoothed by means of a multiple-leaf cavity output mirror[4] or by passage through a matte plate (in which case 30% of the energy was lost). The zone with a uniform intensity was >2 cm in size, because of the decay toward the edges. This zone determined the dimensions of the zone with a uniform gasdynamic effect. In this observation volume, the flow could be regarded as planar, and the radial variations and lateral expansion could be ignored. The conditions of the flow around the object could be varied by varying the initial parameters of the external agent and also by varying the time of detection by the fast dynamic pickups and recorders, combined with time-integrating devices which described the overall process (e.g., the total mechanical momentum). Alternatively, the most interesting phase could be singled out on the basis of maximum development

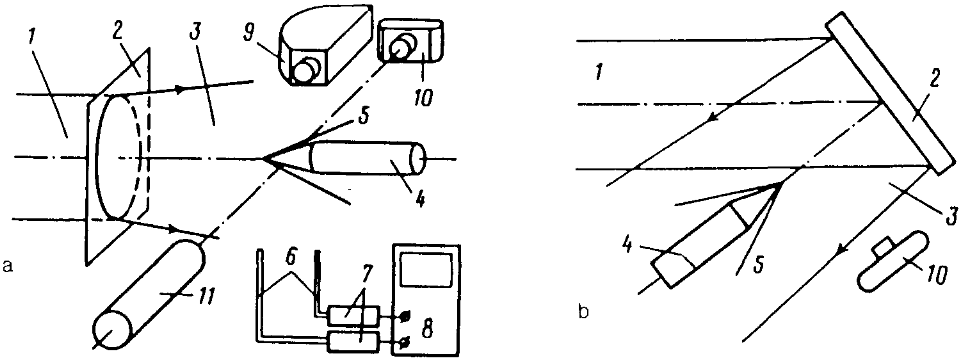


FIG. 1. Experimental layout for gasdynamic studies in a gas flow during the application of a laser beam to a film (parts *a* and *b*) or to the surface of a bulk medium (part *b*). *1*—Pulsed laser beam; *2*—film or surface to be evaporated; *3*—gas flow; *4*—conical object; *5*—shock wave in the flow around the object; *6*—optical fibers; *7*—photomultipliers; *8*—oscilloscope; *9*—VFU high-speed photorecording apparatus; *10*—camera; *11*—OGM-20 ruby laser for recording shadowgrams.

(e.g., by time-integrated photography, which records the process in the phase of the most intense emission).

The experimental layout is shown in Figs. 1a and 1b. The laser beam *1* is incident on a film *2* or the surface of a bulk medium in a vacuum chamber (at a pressure $< 10^{-4}$ Torr; Fig. 1b). The laser beam causes a pulsed high-temperature evaporation, which gives rise to a nearly planar gas jet *3*.

In position *a*, we use an ordinary Lavsan (polyester) film with an aluminum coating $\simeq 10^{-5}$ cm thick facing away from the beam inside the chamber. In position *b* we use either the same film, but with the aluminum coating facing the beam, or the surface of the bulk medium (graphite, aluminum, etc.). In position *b* the laser beam is incident on the surface at an angle of 45°, but the gasdynamic flow is directed outward along the normal to the surface.

To study flow around objects, we placed some small objects in the gas flow: sharp cones (*4*) with vertex angles $2\theta \simeq 15$–30°, a sphere, and planes for studying reflection and deposits. The transverse profile of the gas flow could be varied by varying the transverse profile of the light beam. For example, to produce a tubular flow of annular profile it was sufficient to place a filter or screen at the beam axis.

The method for studying the gas dynamic processes and parameters included the following.

1. Photography was carried out from the side, with the camera (*10*) shutter open.

2. We used a VFU high-speed photorecorder (*9*) with a framing frequency up to 2.5×10^6 s^{-1}.

3. Shadow photographs were taken of the density jumps with the help of an OGM-20 laser (*11*) with a recording by a camera (*10*).

4. A local detection of the emission fronts was carried out with the help of

optical-fiber pickups (*6*) with a directed (collimated) reception of light and with conversion by means of a photomultiplier (*7*). The results were on an oscilloscope (*8*).

Nearly all these methods (other than the shadow photography) recorded the emission or intensified emission of the gas during the flow around the object because of the increase in the gas temperature and density. The shadow photography detected increases in the density of the gas and gradients of the refractive index.

5. Direct mechanical measurements of the momentum transferred to the object, suspended in a ballistic-pendulum arrangement, were also carried out.

6. It also turned out to be possible to detect the structure of the gas flow from traces of condensation left on glass plates in the path of the gas flow.

Description of the gasdynamic processes. During rapid energy evolution, there is an explosive evaporation of a thin layer at temperatures $T > T_{\text{boil}}$ ($\simeq 0.3$ eV for Al). This process may be accompanied by a subsequent heating in a laser discharge with a bulk energy release at a rate $w \simeq n_e e^2 E_0^2 \nu_s / m(\omega^2 + \nu_s^2) \simeq \omega_p^2 E_0^2 \nu_s / 4\pi\omega^2$ with $\omega > \nu_s$ [ω is the frequency of the light, ν_s is the collision rate, n_e is the electron density, and $(E_0^2/4\pi)c = I$ is the power density of the light beam].

The average kinetic energy of the gas flow is determined by the energy which is released. From energy conservation and from the adiabatic equation we find

$$u^2 = \frac{2p_0 x_0}{M_1(\gamma - 1)} \left\{ 1 - \left(\frac{x_0}{x} \right)^{(\gamma - 1)} \right\}$$

and a temperature $T \simeq T_0 (x_0/x)^{(\gamma-1)}$. In other words, the sound velocity in the flow is $c_s^2 \simeq c_{s0}^2 (x_0/x)^{(\gamma-1)}$, where M_1 is the mass of the gas, and x_0 is the initial volume per unit length. We can then immediately find an estimate of the effective Mach number:

$$M^2 = \frac{u^2}{c_s^2} \simeq \frac{2}{(\gamma - 1)} \left\{ \left(\frac{x}{x_0} \right)^{(\gamma - 1)} - 1 \right\}.$$

For $x \gg x_0$ we would have $M = \sqrt{2/(\gamma-1)}\,(x/x_0)^{(\gamma-1)/2}$ and $M_1/M_2 = (x_1/x_2)^{(\gamma-1)/2}$, where the effective adiabatic index γ is approximately 5/3 for a monatomic gas or for a plasma at temperatures which do not approach the ionization or excitation levels. Estimates show that the values $M \simeq 5$–10 which are required can be reached easily within the range $x \simeq 3$–5 cm for $x_0 \simeq 3 \times 10^{-2}$ cm. For our conditions, with $T_0 \simeq 5$ eV, we typically find $u \simeq 10^6$ cm/s and $M \simeq 10$ with an instantaneous gas density $n_a \simeq \rho_{\text{Al}} N_A h / Ax \simeq 3 \times 10^{17}$ cm^{-3}, where ρ is the initial density, A is the atomic weight, h is the thickness of the metallization layer, and N_a is Avogadro's number. This result corresponds to heights ~40 km. The value of x_0 is close to the dispersal distances over the duration of the energy release, $x_0 \simeq u\tau$, where τ is the length of the laser pulse ($\tau \simeq 3 \times 10^{-8}$ s). Different regimes of gas outflow are possible, including some which are limited by the gasdynamics of evaporation alone (without laser breakdown), if the duration of the light pulse is not too long and if the explosion of the film occurs at the end of the pulse. (The explosion time itself may be a small fraction of the pulse duration.) The monatomic nature of aluminum has the further advantage that it does not allow a prolonged deviation from equilibrium of a molecular vibrational nature, and it is more suitable for recalculations for the case of the motion of a fast-moving object in an unperturbed medium.

It also follows that by varying the coordinate or energy of the external agent we can vary the medium which is traversed—from a plasma at small distances of the object from the exploding surface to a rapid unexcited gas for large distances.

The difference between the velocities of the gas behind the front of the fastest motion {a linear change in the velocity along the coordinate, $u=u_{\rm eff}(t)x/x(t)$, is usually reported[5,6] for a given pressure distribution $p[x,t,x_{\rm eff}(t)]$} allows one to expand the range of conditions of flow around the object by choosing a suitable observation time.

The angle (β) between the generatrix of the flow wave around the object and the axis of the thin sharp cone with vertex angle 2θ can be used to estimate the Mach number, from the formula (Refs. 7–10, for example)

$$\frac{\beta}{\theta}=\frac{(\gamma+1)}{(\gamma+3)}+\sqrt{\left[\frac{(\gamma+1)}{(\gamma+3)}\right]^2+\left[\frac{2}{(\gamma+3)}\right]\left(\frac{1}{M^2\theta^2}\right)}$$

which is valid for $M\theta>1$. In the case at hand we have $\theta\simeq 0.23$ rad.

Experimental results. The photographs in Fig. 2 show the following:

a) the integrated flow around a cone with a sharp tip at a distance of 3.5 cm from the film;

b) a shadow photograph of the shock layer taken 3 μs after the laser pulse;

c) oscilloscope traces of signals from two optical fibers, one at a distance of 1.6 cm from the film (the upper trace) and the other at a distance of 2.6 cm from the film (the lower trace), for an applied power density of 3 J/cm^2;

d) frames of the sweep of the VFU with delay times of 1–3 μs, which show the stages of the incidence of the gas flow on the cone, which emits first in the light of film explosion and as a result of the application of the transmitted laser pulse and then, after the transit time, as a result of the incidence of the hypersonic gas flow.

From these results we found a gas velocity $u\simeq 10^6$ cm/s, at $x\simeq 4$ cm and at applied power densities $\simeq 3$ J/cm^2, and a Mach number $M\simeq 10$. These figures correspond to a local sound velocity of 10^5 cm/s and a gas temperature $T\simeq 0.3$ eV (a corresponding estimate from the Saha formula yields a degree of ionization $a\simeq 3\times 10^{-3}$ at a gas density $n_a\simeq 3\times 10^{17}$ cm^{-3}—equivalent to heights $\simeq 40$ km).

The duration of the visible flow around the object was found to be 1.5–2 μs for position 1a. Corresponding results were found for position 1b.

We observed a dependence of the velocity of the gas flow around the object on the laser energy density and a change in the Mach number with the position of the tip of the cone (the Mach number varied from about 10 to 6 as the position of the tip was changed from 4.5 to 2 cm).

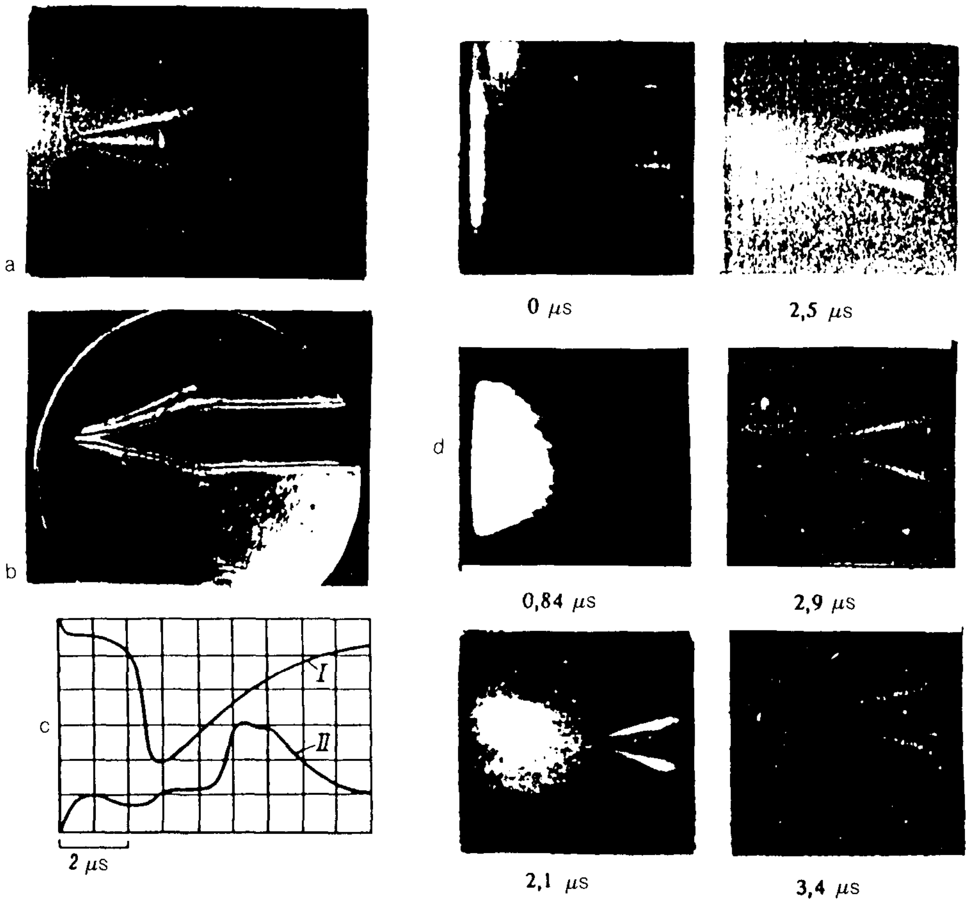
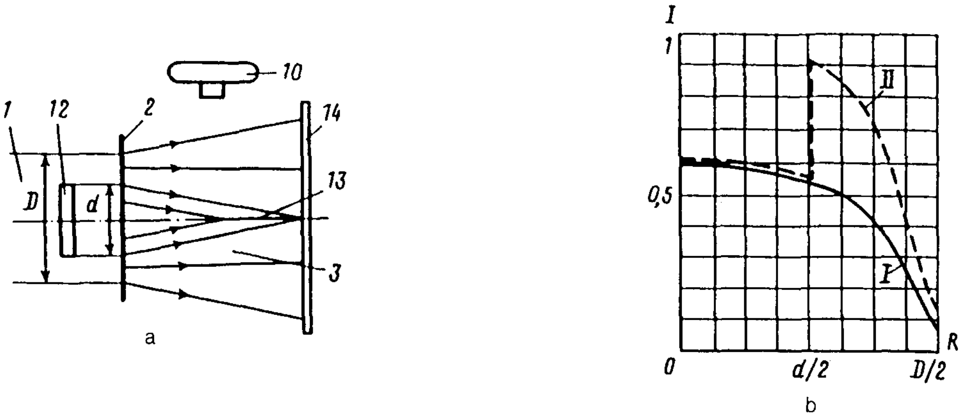


FIG. 2. Photographs of the motion of the gas and the flow around an object. a: Time-integrated photograph of the emission during flow around a cone. b: Shadow photograph of the shock wave during flow around a cone. c: Oscilloscope traces of the detection of the emission of the gas by optical-fiber pickups. The upper trace here corresponds to a fiber at a distance of 1.6 cm from the film, and the lower one to a distance of 2.6 cm. d: Framing photographs of the dispersal of the gas and of the flow of a gas flow around a cone.

We estimated the density and momentum of the gas flow from the momentum transferred to a ballistic pendulum. This pendulum was a small steel ball with a radius $a \simeq 0.2$ cm and a mass of 0.3 g, suspended on a filament of length $l \simeq 10$ cm in a plane 3 cm from the film. This pendulum exhibited a deflection $\simeq 1$ cm. By specifying the mass density of the exploded coating, $M_1 \simeq \rho_{\mathrm{Al}} h \simeq 3 \times 10^{-5}$ g/cm^2 for a coating thickness $h \simeq 10^{-5}$ cm and for a gas velocity $u \simeq 10^6$ cm/s we find the momentum at the cross section of the body of the pendulum to be $M_1 u \pi a^2 \simeq 4$ g·cm/s. From the experiments (from the deflection of the pendulum) we find a momentum $4my/T \simeq 2my/\pi\sqrt{l/g} \simeq 4$ g·cm/s. In other words, the value is very nearly the same. The reason is that the drag of a sphere is approximately one.



a

b

FIG. 3. Shaping of the beam profile and the collapsed gas flow. a: *1*—Laser beam; *2*—film; *3*—gas flow; *10*—camera; *13*—axial condensation of flow; *14*—cover glass for collecting deposits. b: Radial profile of beam intensity. *I*—Beam with large filter; *II*—beam with small filter of same transmission.

Although the gas density in the flow is $\rho \simeq M_1/ut \simeq 3\times 10^{-5}$ g/cm^3 and amounts to hundredths of an atmosphere, the pressure head in the flow at the surface, $p \sim \rho u^2(1-\theta^2)$, ranges from a fraction of an atmosphere to tens of atmospheres, depending on the angle between the flow direction and surface. In other words, it is quite large. It thus becomes possible to use small, high-frequency, thermally shielded piezoelectric pickups to study the local gasdynamic pressure on various regions of objects in the flow.

This method also permits easy and simple "cumulative" experiments, involving the collapse of flows with a nonuniform density or a nonuniform gas heating.

For example, the gas density near the axis can be changed (a tubular flow can be set up) simply by placing a screen or filter of small radius (*12*) near the axis of laser beam (Fig. 3a). In the case of a screen, a solid metallization layer is left behind it on the film (*2*). In the case of a filter, the velocity and density of the gas jet near the axis decrease. In both cases, the decrease in the pressure near the axis results in the beginning of an internal process of inward collapse, which leads to increases in the density and temperature of the gas at the axis.[11-13]

If it is necessary to compare the effect of the flow for a given initial gas pressure at the center but for various pressures at the periphery, one can first use a filter of small radius (the profile of the laser beam is represented by curve *II* in Fig. 3b) and then use a filter of large radius with same transmission (curve *I* in Fig. 3b). Such changes in the intensity distribution simulate gas flow with an annular density or with an annular energy release (annular heating at beginning of uniform flow).

In the time-integrated (Fig. 4a) and framing (Fig. 4d) photography regimes, the experiments immediately reveal (Fig. 4) the appearance of a collapse focus and a line of collapse foci with increases in the emission and the gas density at the axis.

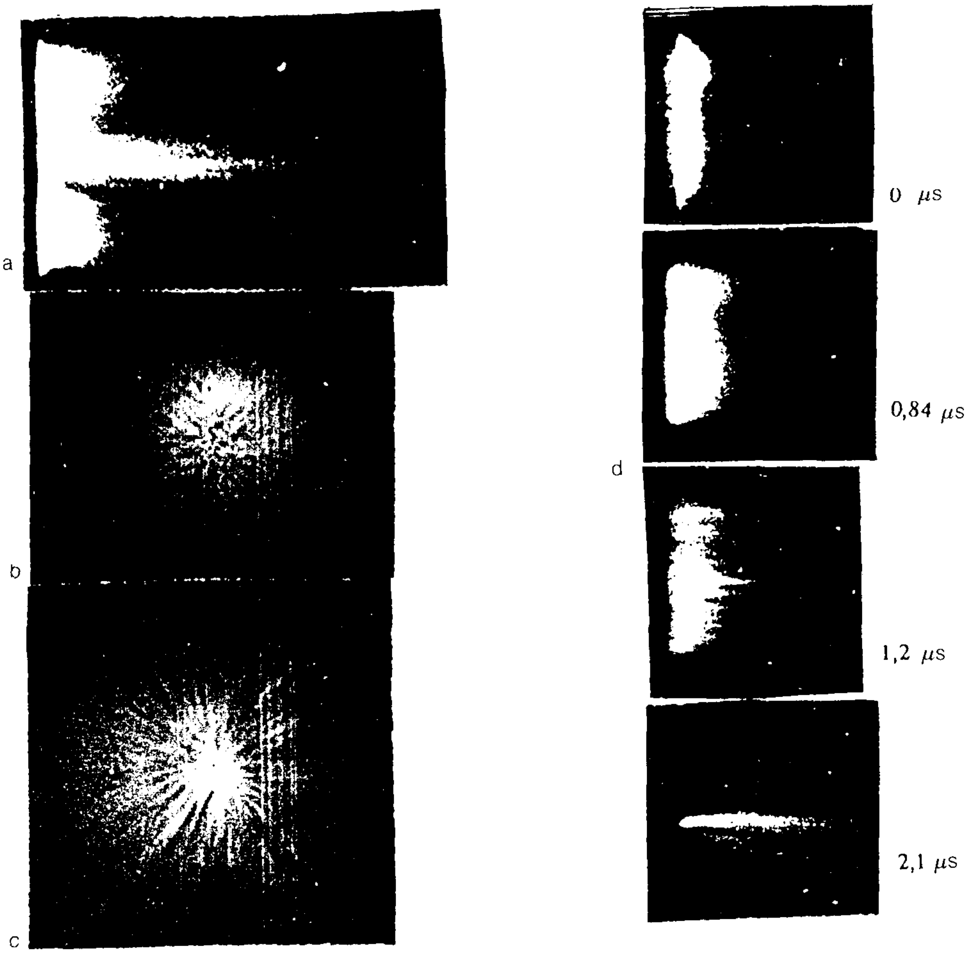


FIG. 4. Photographs of the formation of the collapse of a tubular gas flow. a—Time-integrated photograph from the side; b—deposit on glass plate from a "solid" beam (filter of large diameter); c—deposit from a hollow beam (a bright focus is visible); d—frames of VFU photography of the collapse of hollow flow. The formation of a "cumulation" focus can be seen.

A change in the flow profile during such a collapse was also detected from the pattern of atoms deposited on the glass plate (*14* in Fig. 3a). Although only a small fraction of the atoms are deposited, a single shot is sufficient for the creation of a pattern. In the case of the large filter this pattern is smeared (Fig. 4b), but there is a clearly defined focal spot at this axis (Fig. 4c) in the case of the small filter, which gives rise to a tubular "cumulating" beam.

These experiments demonstrate the wide opportunities for using this method for gasdynamic studies.

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