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# VORTEX FORMATION ACCOMPANYING THE ACTION OF A LASER PULSE ON POLYMERS

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The action of laser radiation on different materials is commonly studied from the point of view of the gas-dynamics of the ejection of products of evaporation or decomposition for short pulses with high energy density [1-4]. These questions have been studied to a lesser extent for radiation densities currently used to study the mechanism of ignition of solid fuels [5-6].

In this work, we study the hydrodynamics of outflow of the products of decomposition of polymers under the action of laser radiation with energy fluxes $q < 10$ kW/cm$^2$. The targets consisted of samples of polymethylmethacrylate (PMMA) and ebonite with dimensions slightly exceeding the characteristic size of the irradiation spot.

The experiments were performed in air at $T = 293$°K and $p = 10^5$ Pa in a closed chamber with a volume of $0.1 \times 0.1 \times 0.3$ m$^3$, equipped with windows for observations and for injecting the laser radiation. The beam from a continuous laser with a wavelength of $\lambda = 10.6$ µm (or $\lambda = 1.06$ µm) was focused from above onto the surface of the material being studied with a spherical mirror; when the mirror was displaced, the diameter of the irradiation spot varied in the range 1-4 mm. The duration of the irradiation pulse was fixed by a mechanical shutter to within 0.2 msec and the density of the incident flux was adjusted in the range 20-10$^4$ W/cm$^2$ by changing either the output power of the laser or the diameter of the irradiation spot.

The flow of the products of decomposition was visualized by the laser-knife method [7] in the stroboscopic regime. For this, the beam from a helium–neon laser was transformed by a system of cylindrical lenses into a plane-parallel beam and was interrupted by an obturator

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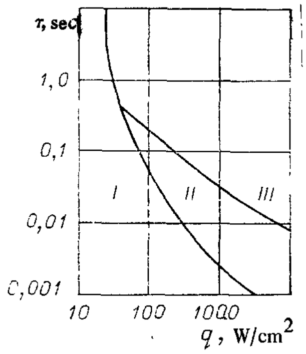


Fig. 1

with a fixed frequency. To observe the characteristic motion of the surrounding medium, a suspension of magnesium oxide particles was created in the chamber. The velocity of the products of decomposition was calculated from the stroboscopic photographs.

The development of the process of irradiation by the laser beam begins with local heating of the surface. As the temperature for the onset of decomposition is reached, gases consisting of the products of evaporation and decomposition, which under certain conditions form a vortex ring, begin to flow away from the location of heating. Figure 1 shows schematically, in particular, for PMMA the regions characterizing these processes in the $\tau$ and q plane, where $\tau$ is the time for which the laser irradiation acts. The region I corresponds to the state of inert heating and is bounded from above by the curve whose form is determined by the thermal conductivity and transparency of the material. In the region II, there is enough time for the temperature of melting and the onset of destruction of the polymer to be reached at the surface and gaseous products with low velocities $u_0 < 0.1$ m/sec, rising upwards, appear above the surface.

A further increase in the pulse duration with fixed q leads to an increase in the velocity of outflow of gas right up to establishment of a constant rate of decomposition [8]. Beginning with Re ~ 5, calculated for air from the diameter of the irradiation spot, the formation of a laminar vortex ring is observed (region III).

Figure 2, where $a$ is the horizontal (PMMA, $\lambda$ = 10.6 μm) and b is the inclined (ebonite, $\lambda$ = 1.06 μm) position of the target (the arrows mark the direction of the laser beam and the direction of gravity), shows motion pictures and photographs which show the sequence of development of ejection of the products of destruction under the action of laser irradiation in this region (two moments, corresponding to the strobe pulses of the laser knife, are fixed in each frame of the film). It is evident that the products of destruction form a vortex ring, analogous to the ring which appears when a portion of gas is pushed out of a pipe with a circular cross section or accompanying the detonation of an explosive [9-11]. In this case, the depth of the crater formed as a result of the outflow of the products of destruction up to the moment of formation of the vortex ring is an order of magnitude smaller than the diameter of the irradiation spot.

The tracks of the microparticles of the suspension (Fig. 3) show that the formation of this vortex, consisting of the products of destruction, is accompanied by the appearance of another, external vortex which consists of the gases from the surrounding medium, has a large diameter, and moves behind the first vortex.

The results of the analysis of the process of formation of the vortex ring from the products of destruction are presented in Figs. 4-6 in dimensionless coordinates, where $R_0$, R, r are the radius of the irradiation spot, the radius of the vortex, and the radius of the transverse cross section of the torus, respectively; $a = R + r$; $u_0$ is the initial velocity of the products of destruction; u is the velocity of the vortex ring; $l$ is the path traversed by the vortex, measured from the surface of the target to the centers of the torus forming over a time t; and $\alpha$ is the angle of inclination of the target relative to the horizon.

Figure 4a and b shows the dependences $u(l)$ and $a(l)$, obtained for ebonite with $\lambda$ = 10.6 μm, q = 500 W/cm², and irradiation times of $\tau$ = 20, 30, 40, 50, and 100 msec, corresponding to curves 1-5. The motion of the vortex formed occurs with an appreciable drop in the velocity $u(l)$ with increasing distance from the target and as the radiation decreases the motion slows down even more (curves 1-4), but up to some value which, once it is attained within the limits of the observed field, becomes uniform. The expansion of the ring $a(l)$

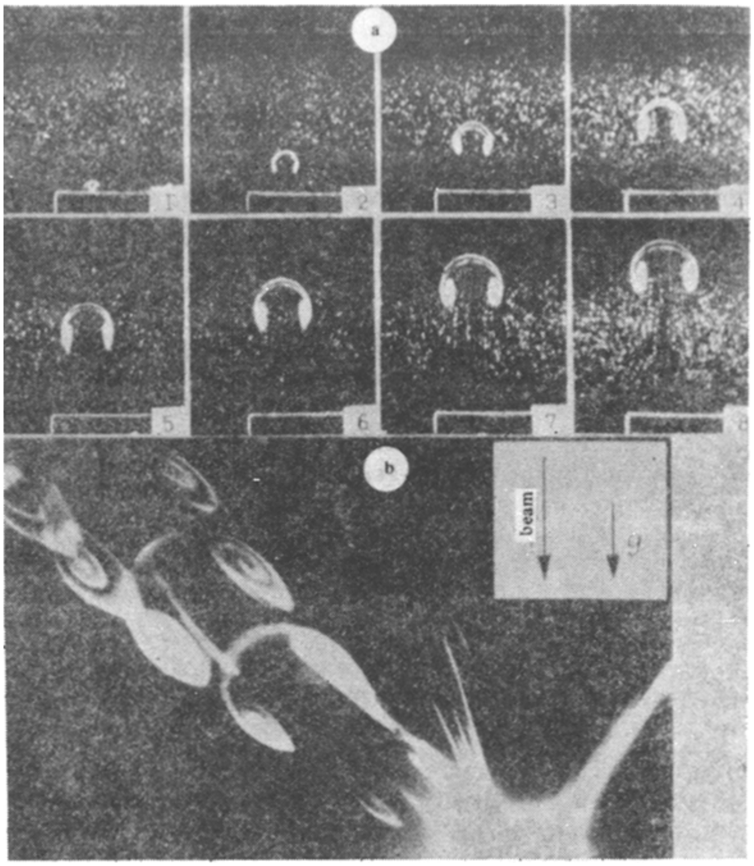


Fig. 2

Fig. 3

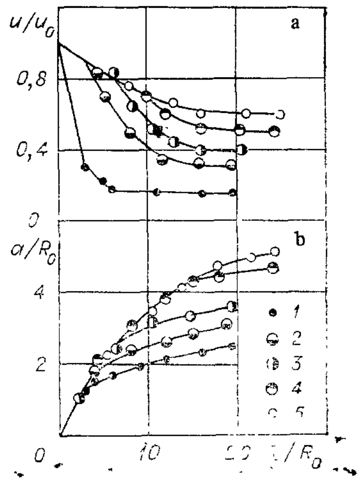


Fig. 4

accompanying the decrease of the radiation also begins to occur at a lower rate than when the ring is fed by the products of destruction.

For any position of the target, the path traversed by the vortex $l(t)$ is independent of the number Re (Fig. 5, where $\tau$ = 0.25 sec; curve 1 for ebonite, $R_0$ = 1.3 mm, $u_0$ = 0.80 m/sec, $\alpha$ = 52°; curve 2 for ebonite, $R_0$ = 2.0 mm, $u_0$ = 0.24 m/sec, $\alpha$ = 67°; curve 3 for ebonite, $R_0$ = 0.6 mm, $u_0$ = 0.35 m/sec, $\alpha$ = 0; curve 4 for PMMA, $R_0$ = 0.6 mm, $u_0$ = 0.20 m/sec, $\alpha$ = 0).

Gravitational forces definitely affect the motion of the vortex. It is evident in Fig. 2b that the products of destruction are initially ejected in a direction normal to the surface of the target, and then the ring which is formed begins to float upwards and is somewhat transformed. The center of the vortex moves along a curved trajectory, and the upper part of the torus grows less intensely because of the worse conditions for capture of products of destruction (Fig. 6, ebonite, $\lambda$ = 1.06 m, $q$ = 2 kW/cm², $\tau$ = 0.25 sec: curves 1 and 2 are

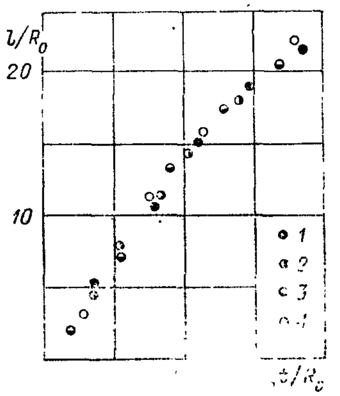


Fig. 5

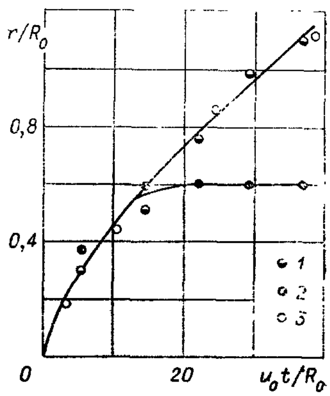


Fig. 6

for the lower and upper, respectively, parts of the torus for $\alpha = 50°$; curve 3 is for the symmetrical vortex). The expansion of the bottom part of the inclined vortex coincides with the expansion for the symmetrical vortex, obtained with a horizontal positioning of the target (curve 3). The effect of the buoyancy force is especially evident when the target is irradiated from below and the vortex formed stops at some distance above the target and then moves upwards and breaks up.

The region of formation of laminar vortex rings is bounded by the flux density $q < 10$ kW/cm$^2$; when this level is exceeded, a turbulent structure of the rings begins to be observed and, at the same time, for weak fluxes of $q \sim 50$ W/cm$^2$, long interaction times lead to breakup of already formed rings by unstable fluxes which catch up with them.

On the whole, the formation of vortex rings accompanying the action of laser radiation is similar to the action observed in [10] in application to semispheroidal vortex rings in liquids with small diameters of the channel of the feed tube.

Thus the action of the ignition pulse on the surface of a polymer causes a vortex structure to form in the gas flow. This structure most undoubtedly affects the conditions of ignition in the gas phase. This problem will be studied in future research.

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