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Application of a high-power KrF laser for the study of supersonic gas flows and the development of hydrodynamic instabilities in layered media

V D Zvorykin, I G Lebo

Abstract. **The design of a miniature laser shock tube for the study of a wide range of hydrodynamic phenomena in liquids at pressures greater than 10 kbar and in supersonic flows with large Mach numbers (greater than 10) is discussed. A substance filling a chamber of quadratic cross section, with a characteristic size of several centimetres, is compressed and accelerated due to local absorption of 100 ns, 100 J KrF laser pulses near the entrance window. It is proposed to focus a laser beam by a prism raster, which provides a uniform intensity distribution over the tube cross section. The system can be used to study the hypersonic flow past objects of complex shape and the development of hydrodynamic instabilities in the case of a passage of a shock wave or a compression wave through the interfaces between different media.**

1. Introduction

The stability of an interface between two media found in the field of constant or pulsed acceleration is a fundamental problem of fluid and gas mechanics. In the first case, the contact surface is unstable if the gradients of pressure and density have opposite directions. In particular, the instability of this kind (Rayleigh – Taylor instability) occurs in the gravitation field, provided a heavier fluid is found above a lighter one [1]. In the case of pulsed acceleration caused by the passage of a shock wave through a contact surface between two liquids or gases or a sharp deceleration of a substance, which previously moved, the interface is unstable for any arrangement of layers. This kind of instability (Richtmyer – Meshkov instability) leads to a rapid evolution of initially weak perturbations into turbulent mixing of contacting media [2, 3].

The study of the evolution of hydrodynamic instabilities is a problem of great importance in inertial fusion (see, e.g., Refs [4 – 6]), physics of high energy densities, cosmology, and astrophysics [7 – 8]. The passage of strong shock waves through contact surfaces of two gases with different densities causes the formation and development of complex vortex structures, which are of interest for present-day nonlinear hydrodynamics and for studying the problem of a change from an ordered state to chaos [9, 10]. Another problem, which is important for the development of modern aerospace engineering and protecting the Earth from collisions with space objects, is the study of a supersonic flow past bodies of complex shape at large Mach numbers.

The problems mentioned above are studied by numerical methods using 2D and 3D simulation codes (see, e.g., Refs [11 – 14]), in laboratory experiments with shock tubes [3, 15-17], special rocket facilities [18, 19], and using high-power lasers [20 – 22] and explosions [17, 23]. Experiments in gases in shock tubes are carried out at relatively small Mach numbers $M = 1 - 4$ (here, the Mach number is the ratio of the shock wave velocity to the sound velocity in an unperturbed gas) and pressure amplitudes of about 10 bar. Facilities with rocket accelerators allow one to study Rayleigh – Taylor instabilities at a contact surface between two fluids upon quasi-stationary accelerations exceeding the acceleration of gravity g by a factor of $10^2 - 10^3$. Even greater accelerations ($10^4 g$) are realised in special explosive chambers in front of the leading edge of a combustion wave in gas media [24].

Explosion and laser experiments enable one to obtain very high pulsed pressures in a condensed substance and a plasma, as high as $\sim$100 kbar with the aid of chemical explosions and as high as $\sim$100 Mbar with the aid of nuclear explosions and unique laser facilities with the highest power. Any explosion experiment has the following disadvantages: Some equipment in each experiment is destroyed; the experimental conditions are poorly reproduced; and one has to ensure that the experiments are safe, which is possible only in specially equipped laboratories.

Lasers are used to study hydrodynamic flows and instabilities in plane, cylindrical, and spherical geometries, both in the case of direct target heating and in the case of converting laser radiation to x-rays, which enables one to improve irradiation uniformity. However, the multichannel and multielement laser facilities used for this purpose, such as ISKRA-5 (Russia), VULCAN (Great Britain), NIKE, NOVA, and OMEGA (USA), and GEKKO XII (Japan), with radiation energy of the order of 10 kJ, and the megajoule facilities NIF (USA) and LMJ (France), which are now being built, are extremely expensive.

In typical laser experiments, the radiation intensity q in a focal spot of size 100 – 1000 μm is $10^{13} - 10^{15}$ W cm^{-2}, and the pulse duration is of the order of 1 – 10 ns. In this time, a shock wave travels in a solid path 10 – 100 μm long, which determines the characteristic scale of a phenomenon being studied, because the unloading wave rapidly weakens the shock wave after the termination of a laser pulse. The development of instability in condensed media, as a rule, is studied with complex and expensive x-ray techniques, which often give only time- and space-integrated information.

V D Zvorykin, I G Lebo P N Lebedev Physics Institute, Russian Academy of Sciences, Leninskii pr. 53, 117924 Moscow, Russia

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In this paper, we propose a new technique for exciting shock waves in gases and compression waves in liquids by a pulsed laser with a considerably lower radiation energy ($\sim$100 J) for modelling a wide range of hydrodynamic phenomena mentioned above at a spatial scale of $\sim$1 mm in a range of microsecond durations. The idea is based on two known facts:

(1) Lasers with this energy and pulse duration of 10 – 100 ns, when irradiating the surface of a solid coated with a thin layer of a transparent dielectric, which hampers a rapid unload of the evaporated substance, produce compression waves with amplitudes of $\sim$10 kbar in solids at moderate radiation intensities $q = 10^8 - 10^9$ W cm^{-2} [25, 26]. In this case, the transverse size of the loaded region may be about 1 cm, and the maximum pressure is limited by the optical breakdown of the dielectric. Instead of a transparent dielectric, one may use water, which is transparent not only for IR radiation of a Nd laser [27] but for UV radiation of a KrF laser as well.

(2) These intensities are quite sufficient to excite strong shock waves with Mach numbers $M \geqslant 5 - 10$ in the atmospheric air surrounding a target, and their damping law, which is described by the model of strong explosion, is determined by the geometry of an experiment, i.e., by the ratio of the size of a laser spot on the surface to the distance passed by the shock wave [28].

2. Design of a laser shock tube

In the system considered here, the confinement of a laser-produced plasma and the excitation of plane shock waves take place inside a miniature tube, which restricts lateral unloading. The design of such a laser shock tube is based on the use of the following basic components: a shock tube chamber; a KrF laser; a laser focusing system; and 2D numerical codes.

The schematic of the shock tube is shown in Fig. 1. Laser radiation enters through a transparent window 1 inside a chamber of square cross section, which is filled with a liquid or a gas*. Radiation is absorbed in a thin layer 2 adjacent to the window (Fig. 1a), resulting in a compression wave travelling in both directions from the energy release region. Because the chamber with focusing optics can be arbitrarily oriented with respect to the horizon, one can study in it the behaviour of the inclined interface between different immiscible liquids accelerated in the compression wave.

Initial perturbations on the contact surface between two liquids or a liquid and a gas can be also produced by a piezoceramic transducer 7 attached to the chamber wall. In the case of a gas (Fig. 1b), a thin layer of a nontransparent substance 2, which initiates a strong shock wave 6, is deposited onto the rear window surface for efficient absorption of laser radiation. One can place liquid drops or solid particles of different shape inside the chamber to study the hypersonic gas flow accelerated in a shock wave past these objects. Because the liquids and gases under study are transparent to probing visible radiation, one can use conventional high-speed shadow and schlieren photography [28, 29] to visualise and study the spatial and time evolution of a flow in the laser shock tube.

A GARPUN KrF laser with energy up to 100 J and pulse

*A window may be replaced with a layer of water, provided the tube chamber is oriented vertically and radiation is injected from the top.

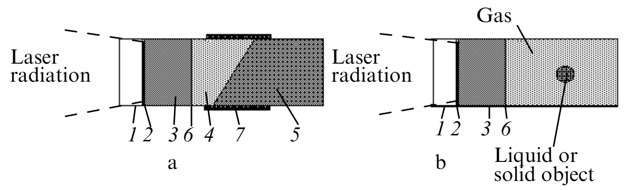

Figure 1. Schematic of the shock tube for studying (a) the development of Richtmyer – Meshkov instability and (b) specific features of a supersonic flow past objects of complex shape. (1) A silica glass plate or a layer of water transparent to laser radiation; (2) nontransparent thin layer; (3) region loaded by a shock wave; (4) unperturbed first medium (a gas or a liquid); (5) unperturbed second medium (a gas or a liquid); (6) front of a shock wave (or a compression wave); (7) piezoceramic transducer.

length of 100 ns [29] emits UV radiation at 0.248 μm, which is strongly absorbed in different liquids [30] and the plasma produced by it, which substantially affects the amplitude of a generated pressure pulse [28]. Moreover, the exit window of the shock tube, which is made of silica glass, has high thresholds of optical breakdown for the surface in air and the bulk of the medium, and their experimental values are 2.5×10^9 and 10^{10} W cm^{-2}, respectively [31]. These two factors determine the choice of a KrF laser as the best driver for the given system. A neodymium laser has close thresholds of the entrance window breakdown, but its radiation is absorbed more weakly in the liquids under study. As for a CO_2 laser, its application is substantially restricted by a low radiation resistance of the entrance window and strong reflection of radiation from a dense plasma [28].

The system of laser radiation focusing by a multielement prism raster [32], which consists of a large number of prisms, splits the initial large-aperture laser beam of transverse size 16×18 cm into several dozens of separate small-aperture beams of size 2×2 cm and efficiently mixes them in the focal plane. This enables one to focus a laser beam into a square, highly uniform spot with the intensity of $\sim (2 - 5) \times 10^8$ W cm^{-2} even in the case of strong aberrations. The uniformity obtained in the laser intensity distribution at the entrance to the shock tube determines the initial perturbations at the front of a laser-produced shock wave.

To calculate the hydrodynamic processes in Lagrangian [33] and Euler [34] coordinates, we used 2D numerical codes, which allow us to model the development of instabilities and describe the phenomena being observed in detail.

3. Numerical simulation of the propagation of pressure waves in the laser shock tube

The numerical calculations modelling the formation and propagation of a pressure wave in the laser shock tube were made using the ATLANT code [33] in the cylindrical geometry. A laser beam travelled along the z axis. We analysed three cases: the formation of a compression wave and its propagation in a long channel filled with water, the propagation of a compression wave and the acceleration of the kerosene-water interface under the action of this wave, and the propagation of a shock wave in a gas. In all cases, the calculated region was 12 cm long. In the first case, the first subregion was filled with water with an initial density of 1 g cm^{-3}; in the third case, it was filled with gaseous xenon with an initial pressure of 5.4 mg cm^{-3}. This subregion was 10.5 cm long. In the second case, water occupied a subregion 10 cm long, and kerosene (with an initial density of

0.8 g cm^{-3}) occupied a subregion 0.5 cm long. Behind them, a thin 2 μm layer of aluminium with an initial density of 2.7 g cm^{-3} and a layer of silica glass 0.5 cm thick with an initial density of 2.5 g cm^{-3} were positioned.

Laser radiation was incident from the right, passed through a transparent layer, and was totally absorbed in an aluminium layer. A KrF laser pulse had a trapezoidal form, with leading and trailing edges 20 ns long and a region of constant intensity 3.1×10^{8} W cm^{-2} 60 ns long. The calculations were made in the quasi-one-dimensional approximation; i.e., we ignored the nonuniformity of physical quantities in the transverse direction. The expression for the pressure of a condensed medium had the form [35]

$$P = P_{\rm c} + P_{\rm t} - P_i^0 ,$$

$$P_{\rm c} = \begin{cases} \dfrac{\rho_0 C_{\rm s}^2}{n}\left[\left(\dfrac{\rho}{\rho_0}\right) - 1\right] & \text{for } \dfrac{\rho}{\rho_0} \geqslant 1, \\ 0 \quad \text{for } \dfrac{\rho}{\rho_0} < 1 , \end{cases}$$

where $P_{\rm t}$ is the thermal pressure of an ideal gas, n is a variable parameter, ρ_0 is the initial density of a condensed medium, and $C_{\rm s}$ is the sound velocity in this medium. To equalise the initial pressure in all regions, we introduced a constant P_i^0 for each subregion (i is the subregion number).

The heat of metal sublimation is $1-10$ kJ g^{-1} [36], which gives an energy of $1-10$ J for a foil of mass $\sim 10^{-3}$ g, with absorbed energy equal to 100 J. In the calculations presented here, we ignored the energy loss through melting and evaporation of an absorbing layer.

Fig. 2 presents the spatial distributions of pressure at different moments of time. Because of heating and evaporation of a thin aluminium layer, a pressure jump with the amplitude greater than 10 kbar occurred and a compression wave was produced, which travelled in both directions from the energy release region. As the wave travelled in water, the pressure amplitude decreased. At a moment of 700 ns, by which the wave travelled a path ~1 mm long, the pressure amplitude was $3-4$ kbar, and the compression ratio of the medium was $\rho/\rho_0 \sim 1.3$ (Fig. 2c). Every 4 μs, the wave travelled more than 5 mm, and the pressure decreased down to 1.5 kbar. Note that the parameters presented above were weakly dependent on the form of the equation of state used for the substance in the calculations. The calculations presented here were made for $n = 4$. In the case of calculations made for $n = 10$, the compression ratio decreased, and the pressure amplitude increased by $5 - 10\%$.

Fig. 3 presents results of the calculation of the passage of the compression wave through the kerosene-water interface. The contact layer acquired pulsed acceleration, which exceeded the acceleration of gravity g by a factor of $10^6 - 10^7$. Figs 3b and 3c show the distributions of velocity and pressure along the z axis at different moments of time. As the wave passed through the contact surface, the pressure was ~ 1 kbar, and the velocity increased up to 100 m s^{-1}. In the case where the tube is completely filled with liquids, the interface displacement is small.

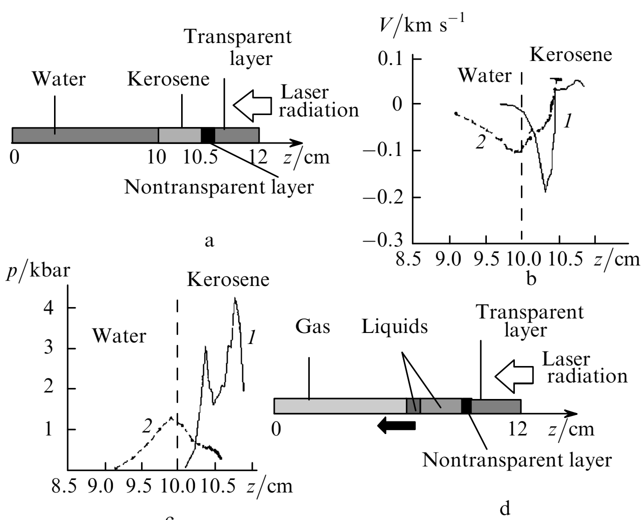

Figure 3. Results of the calculation of the propagation of a shock wave through the kerosene-water interface. (a) Schematic of the experiment; the distributions of (b) velocity and (c) pressure along the z-axis at moments of time $t = 1$ (1) and 4.7 (2) μs. (d) Schematic of the experiment on the study of instability development in the case of acceleration of two thin liquid layers in the tube; the black arrow specifies the direction of motion.

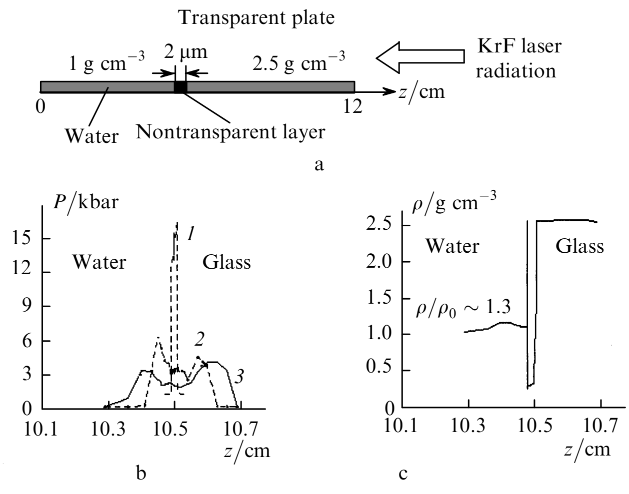

Figure 2. Results of the calculation of the propagation of a compression wave in water. (a) Schematic of the experiment; (b) the pressure distributions at moments of time $t = 50$ (1), 375 (2), and 700 ns (3); and (c) the density distribution at the moment of time $t = 700$ ns.

To increase the 'braking distance' of the interface and, consequently, the instability development time, it is advantageous to place two thin liquid layers ($0.5-1$ cm thick) into the tube and to fill the greater spatial region with a vapour (the second layer may consist of a jelly [37] or a solid material loosing elasticity under loads much lower than 1 kbar; in this case, one may orient the shock tube vertically and inject radiation from its top). At the stage of acceleration of a medium by a pressure pulse, the instability is developed at the interface between two liquids; and at the stage of deceleration by a compressed gas, the instability is developed at the liquid-gas interface.

Fig. 4 shows results of the calculation modelling the propagation of a shock wave in xenon. The sound speed in xenon and glass was 174 m s^{-1} and 3.7 km s^{-1}, respectively. One can see that a strong shock wave with Mach numbers $M \sim 40$ is formed in the gas, and this wave gradually damps during its propagation. By a moment of 700 ns, it travels a 4 mm path, but its velocity remains rather high and corresponds to $M \geqslant 20$. The supersonic propagation of the shock wave and the gas behind its front was observed in

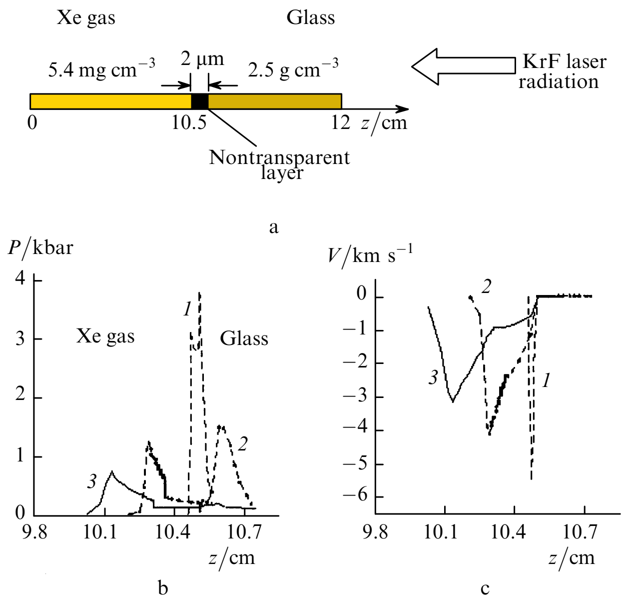

Figure 4. Results of the calculation of the propagation of a shock wave in a gas. (a) Schematic of the experiment; the distributions of (b) pressure and (c) velocity along the z-axis at moments of time $t = 80$ (1), 362 (2), and 700 ns (3).

the calculations during several microseconds over distances several centimetres long.

4. Conclusions

The technique proposed here for exciting shock waves in gases and compression waves in liquids by KrF laser radiation has some advantages in comparison with the conventional technique used in experiments with nanosecond laser pulses. The typical scale of gas-dynamic flows is of the order of 1 mm, and the duration of processes reaches several microseconds. This enables one to use conventional optical techniques to observe the spatial and time evolution of instabilities at the interfaces between different media and to study the supersonic gas flow past objects of complex shape. One can also study the effect of a repeated initiation of acceleration by several shock waves, which are produced by a tandem of laser pulses separated by a variable delay, on the instability development. In the case of two contacting liquids, one can use laser radiation to produce accelerations exceeding the acceleration of gravity by a factor of 10^6 and to study the development of hydrodynamic instabilities under such conditions.

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