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Study of the hydrodynamics of the formation of flows caused by the interaction of a shock wave with two-dimensional density perturbations on the Iskra-5 laser facility*

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Abstract. **The hydrodynamics of the flow formation due to the interaction of a shock wave with two-dimensional density perturbations is experimentally investigated on the Iskra-5 laser facility. Shadow images of a jet arising as a result of the impact of a shock wave (formed by a soft X-ray pulse from a target-illuminator) on a flat aluminium target with a blind cylindrical cavity are recorded in experiments with point-like X-ray backlighting having a photon energy of ~4.5 keV. The sizes and mass of the jet ejected from the aluminium cavity by this shock wave are estimated. The experimental data are compared with the results of numerical simulation of the jet formation and dynamics according to the two-dimensional MID-ND2D code.**

Keywords: *shock wave, density perturbation, jet, X-rays, X-ray backlighting.*

1. Introduction

The development of high-performance computers makes it possible to implement software packages for solving two- and three-dimensional hydrodynamic problems in different fields of national economy. Here, an urgent task is to search for the conditions under which one can obtain experimental data for testing developed complexes and methods of 2D and 3D simulation on parallel supercomputers. High-power laser systems provide experimental conditions for simulating the dynamics of two- and three-dimensional flows arising as a result of the formation of jets with a high Mach number under the action of shock waves with a pressure of several megabars. This simulation of two- and three-dimensional flows, which has constantly been performed by American researchers, started with the experiments on the NOVA facility [1], was continued on the OMEGA facility [2], and is planned to be continued on the NIF facility [3].

The software packages developed at the VNIIEF for solving two- and three-dimensional hydrodynamic problems can be experimentally verified, in particular, by measuring a number of parameters (spatial sizes, characteristic velocities, mass of the jet, and its spatial distribution) in experiments carried out on laser systems. Unfortunately, such a verification cannot be performed based on the results of known experiments [1–3] because of the lack of information.

In this paper, we report the results of the experimental study of the formation of flows upon interaction of a shock wave with two-dimensional density perturbations in the form of a cylindrical cavity. The experiments were performed on the Iskra-5 laser facility. The obtained data were compared with the results of simulation using the two-dimensional MID-ND2D code, developed at the VNIIEF.

2. Experiment statement

A schematic of the experiments aimed at studying the hydrodynamics of the flow formation upon interaction of a shock wave with a density perturbation in the form of a blind cylindrical cavity in a flat disk by X-ray backlighting using a quasi-point radiation source is presented in Fig. 1.

Four or six (as in Fig. 1) laser beams from the Iskra-5 facility are launched into a target-illuminator to convert the laser energy into the energy of quasi-Plankian X-rays. The soft X-rays generated in the illuminator form a shock wave in the sample under study. The sample is a plate with a cylindrical cavity on its rear surface. The shock wave propagates through the sample, heating it to the plasma state. The plasma from the cavity walls fills the cavity. As a result, a jet is formed, which propagates along a shock tube filled with a low-density foam. The jet motion is recorded by backlighting X-rays from a point-like X-ray source through the shock tube at a specified instant. To protect a recorder from the X-rays emitted from the target assembly, a screen with a trapezoidal window (for observing the jet propagation region) is installed on it. The protection from the X-rays emitted from the holes for the laser beam input is provided by installing an additional protective V-shaped screen between the laser beams (near the target).

The target-illuminator and the target of the X-ray backlighter were irradiated by the second harmonic of laser radiation. The X-ray backlighter was illuminated with a specified delay with respect to the instant of target-illuminator heating.

Contrast shadow images of jets were obtained using X-ray lines from titanium (photon energy $h\nu \approx 4.75$ keV) or scandium ($h\nu \approx 4.32$ keV) targets. The X-ray lines were selected using a 20-μm-thick titanium filter.

The shadow target image was recorded on a UF-4 X-ray film with a magnification of $M \approx 8$. To determine the latter, a

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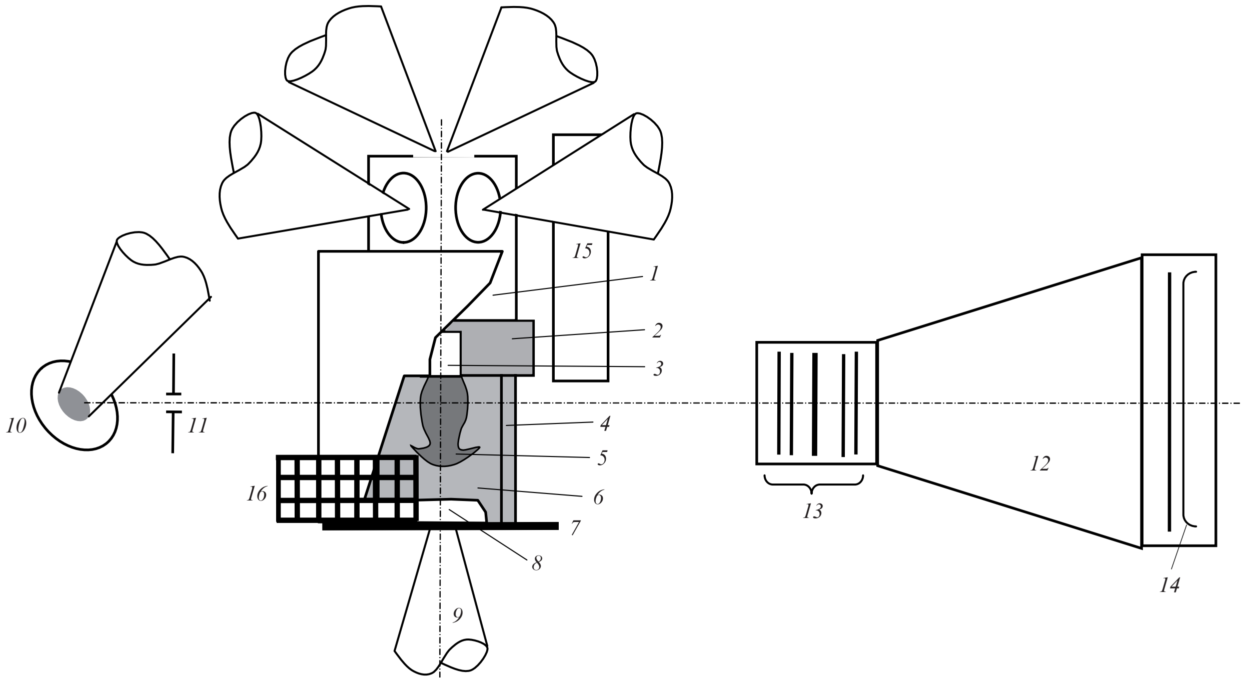

Figure 1. Schematic diagram of the experiment aimed at studying the hydrodynamic flows: (*1*) target illuminator; (*2*) sample; (*3*) cylindrical cavity; (*4*) shock tube; (*5*) jet; (*6*) foam; (*7*) flange; (*8*) screen with a trapezoidal window; (*9*) target holder; (*10*) X-ray backlighting target; (*11*) pinhole; (*12*) recorder; (*13*) set of filters; (*14*) X-ray film; (*15*) additional V-shaped protective screen; (*16*) graticule.

grid with 130-μm meshes was installed on the target in some experiments.

3. Target design

The front view of the target assembly and its side view are shown in Fig. 2. The target-illuminator is a cylinder 650 μm in diameter and 900 μm in length; its wall is made of a 14-μm-thick polyparaxylelene (PPX) film. The illuminator blind end face was closed by a 20-μm-thick aluminium flange. Laser radiation was injected through four holes 300 μm in diameter, located on the illuminator lateral surface symmetrically along its perimeter. To provide efficient conversion of laser radiation into X-rays, the inner surface of the illuminator and the Al flange were coated, respectively, with 2.7- and 1.5-μm-thick layers of gold (material with a high atomic number).

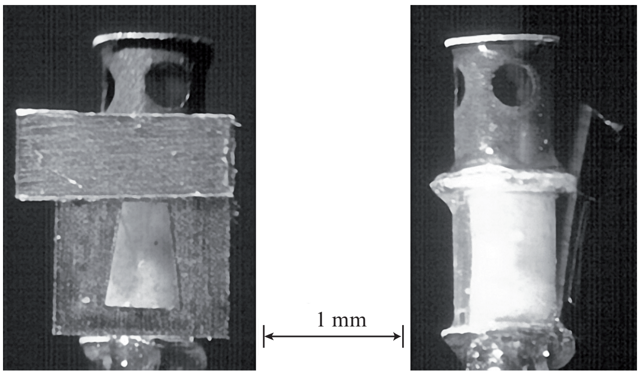

Figure 2. (a) Front view of the target assembly (along the X-ray backlighting) and (b) the side view.

The sample under study consisted of two Al disks, closely pressed toward each other and glued with an epoxy glue along their perimeter (Fig. 3). One disk (50 μm thick) was continuous (without a hole), while the other had a through cylindrical hole with a diameter approximately equal to the disk thickness.

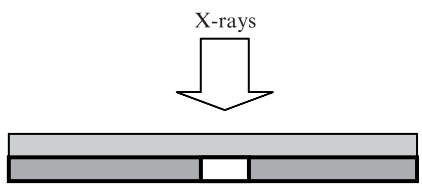

Figure 3. Schematic of the Al sample.

The housing of the shock tube 670 μm in diameter and 930–950 μm in length was made of a 12-μm-thick PPX film. The tube was filled with a polymethylmethacrylate foam having a density $\rho \approx 1.2\times10^{-2}$ g cm^{-3}. A cylindrical foam sample was closely attached to the Al disk and glued to it at several points; the other sample end was free. The tube end was closed with a flange 1 mm in diameter, onto which the target holder was mounted.

To form a point X-ray backlighter, we used a pinhole with a diameter of 20 μm, made of a Ta foil about 25 μm in thickness. An additional diaphragm made of a 100-μm-thick Ta foil with a diameter of 140 μm was installed on it to reduce the intensity of the background X-rays transmitted through the diaphragm and increase the shadow image contrast. To protect the diaphragms from the laser radiation scattered from the backlighter, they were covered with a 6-μm-thick Lavsan film.

4. Experimental results

We performed a series of experiments on targets with cavities of different sizes in the Al sample; the cavity diameter approximately corresponded to the cavity depth. The laser energy on the target varied from 0.8 to 1.2 kJ. The instant of target backlighting was delayed by 15 ns. Previous experiments [4] showed that the aforementioned laser radiation parameters made it possible to reach the X-ray temperature in the converter box as high as $T_X \approx 150 \pm 10$ eV.

Examples of experimental shadow images of jets are presented in Fig. 4.

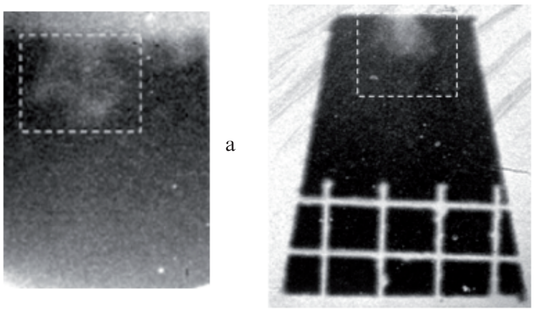

Figure 4. Results of X-ray backlighting of targets. (a) Experiment 2: $E_{LE} \approx 1.1$ kJ, cavity sizes $\varnothing 90\times95$ μm, backlighting from a Ti target ($h\nu \approx 4.75$ keV). (b) Experiment 4: $E_{LE} \approx 0.8$ kJ, cavity sizes $\varnothing 200\times200$ μm, backl;ighting from a Sc target ($h\nu \approx 4.32$ keV). The dashed lines outline the rectangular regions in which a jet shadow is observed; the grid mesh size is 130×130 μm.

By the instant of backlighting, the jet has a mushroom-like shape in both cases. In the upper part of the image recorded in experiment 2, one can see a diffuse boundary of the pedestal formed by the shadow image of the aluminium mass ejected by the shock wave from the rear (with respect to the illuminator) surface of the Al disk with a hole. The width of the jet base practically coincides with the diameter of the hole in the Al disk (90 μm). The jet vertex is spaced from the pedestal by ~180 μm and has a large width, also about 180 μm. In experiment 4, the width of the jet base is ~100 μm, which is about half the diameter of the hole used in this experiment. The jet vertex is spaced from the pedestal by 100–120 μm and has a width of about 180 μm. Since the recorded images have a low contrast, the above jet sizes are only estimates. Nevertheless, they are indicative of the influence of the cylindrical hole size on the character of the jet formation by the probing instant.

The Al mass in the jet was estimated by processing the images using the relation

$$m_{Al} = -\frac{1}{\mu_{Al}}\sum \ln\frac{I(r)}{I_0(r)}\left(\frac{\Delta x}{M}\right)^2, \tag{1}$$

where $I(r)$ and $I_0(r)$ are, respectively, the intensities of the shadow image and the backlighting radiation at the corresponding points within the chosen image fragment [$I_0(r)$ was determined on the entire fragment by linear interpolation of its values on the left and right boundaries of the image]; Δx is the image scanning step; $M = 8$ is the magnification factor, with which the shadow jet image was recorded; and μ_{Al} is the X-ray absorption coefficient in aluminium, which was assumed to be equal to that for cold aluminium at the probe photon energy. In experiment 2, at the cavity sizes of $\varnothing 90\times95$ μm, the mass m_{Al} of the jet ejected by the shock wave from the cavity turned out to be about 0.1 μg. In the experiment with cavity sizes of $\varnothing 200\times200$ μm, $m_{Al} \approx 0.06$ μg.

5. Development of the two-dimensional model of jet formation

In the case of one-dimensional simulation, the possibilities of analysing the evolution of gas-dynamic instabilities and the influence of the asymmetry effects on the final parameters are highly limited or even absent. At the same time, time-dependent and nonequilibrium effects, which are characteristic of laser plasma, significantly affect the dynamics of target motion and the evolution of perturbations. In view of the aforesaid, it is necessary to develop multidimensional techniques in order to expand the possibilities of the laser plasma simulation.

To date, a two-dimensional MID-ND2D code has been developed at the VNIIEF, which makes it possible to carry out (for a reasonable time) mathematical simulation of experiments on laser facilities.

The MID-ND2D code makes it possible to simulate a large number of physical processes, such as the laser radiation propagation and laser energy absorption, the gas-dynamic motion of plasma in the multitemperature approximation, electron and ion thermal conductivity, spectral transport of X-rays, thermonuclear reactions, and energy transfer by α particles.

Using the MID-ND2D code, we performed a series of test calculations to simulate the experiments on studying the hydrodynamics of the formation of two-dimensional flows with the sample parameters used in experiment 2 (cavity sizes $\varnothing 90\times95$ μm). In these calculations for the real target design (without the illuminator), we set an X-ray flux with the maximum equilibrium temperature $T_X = 140$ or 160 eV from the end face. Figure 5 shows the calculated distributions of optical thicknesses (integral of the jet material density along the observation direction) at the instant $t = 14.9$ ns. The calculated jet parameters are listed in the table.

The comparison of the calculation results with the experimental data shows that, for the cavity $\varnothing 90\times95$ μm in size, the calculated geometric jet sizes at the probing instant are twice as large as the experimental values, and the aluminium mass in the jet is larger by a factor of 5–10. The difference in the sizes can partly be due to the fact that the simulation was per-

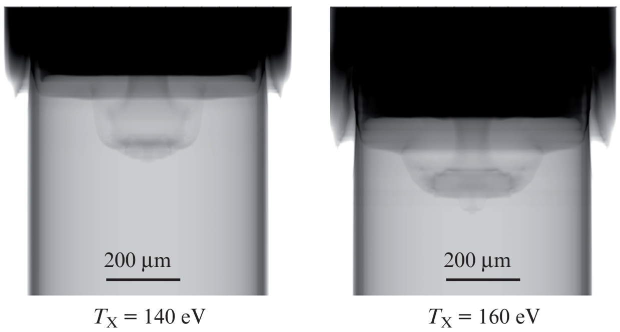

Figure 5. Calculated distributions of the optical thickness in the jet at the instant $t = 14.9$ ns for two temperatures T_X; the cylinder diameter is 700 μm.

Table 1. Jet design parameters.

T_X/eV	t/ns	m_{Al}/μg	h/μm	r/μm
140	13	0.55	227	114
	14.9	0.59	240	128
160	13	0.64	253	156
	14.9	0.67	266	185

Note: m_{Al} is the mass of Al in the ejected jet; r is the jet radius; and h is the spacing between the jet and pedestal.

formed without calculating the shadow X-ray image with allowance for the temperature and density distributions in the jet. In addition, it was suggested that there may be a technological gap between the two layers of the sample with cylindrical cavity, which reduces the efficiency of the shock wave transition from the continuous plate (the irradiation of which induces a shock wave) to the second plate with a cylindrical cavity, where a jet should be formed.

One must also take into account the following circumstance. When processing the experimental results, the jet mass was estimated proceeding from the absorption coefficient of probe X-rays in cold rather than heated aluminium. The X-ray absorption coefficient of cold aluminium, μ_{Al}, in the vicinity of $h\nu \approx 4.5$ keV is larger than that of heated Al; therefore, the jet mass found from formula (1) is underestimated.

In this stage of studies, the above-mentioned differences between the preliminary calculation results and the experimental data can be considered as quite satisfactory.

6. Conclusions

A series of experiments aimed at studying the formation and evolution of hydrodynamic flows in the presence of two-dimensional density perturbation in the form of a cylindrical cavity was performed on the Iskra-5 laser facility.

The experiments were carried out on aluminium samples with cylindrical cavities having different sizes: ∅100×100, ∅150×150, and ∅200×200 μm. The samples were heated by soft X-rays with an effective temperature $T_X \approx 150$ eV from target-illuminators irradiated by four or six laser beams with $\lambda = 0.66$ μm and total energy ranging from ~760 to ~1200 J.

To carry out the experiments, we prepared targets with a grid and improved the design of the point-like X-ray backlighter in order to increase the shadow image contrast. X-ray shadow images of the jet were obtained with energies $h\nu \approx 4.75$ keV of X-ray photons from a Ti target and $h\nu \approx 4.32$ keV of X-ray photons from a Sc target.

For an aluminium cavity with sizes of ∅90×95 μm, the mass m_{Al} of the jet ejected from it under the action of a shock wave formed by soft X-rays from the target-illuminator, with the coupled laser energy of about 1.1 kJ, was estimated to be ~0.1 μg. For a cavity ∅200×200 μm in size and laser energy of 0.8 kJ, the estimated jet mass was about 0.06 μg.

The preliminary results of the numerical simulation of the jet formation and evolution, based on the two-dimensional MID-ND2D code, showed that the jet parameters depend strongly on the probing instant. The simulation results for a cavity ∅90×95 μm in size predict that, by the probing instant, the jet geometric sizes should be twice as large as in the experiment, while the aluminium mass in the jet should be larger by a factor of 5–10. In this stage of studies, these discrepancies between the preliminary calculation results and experimental data can be considered as quite satisfactory.

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