Journal of Applied Mechanics and Technical Physics, Vol. 41, No. 5, 2000

EXPERIMENTAL INVESTIGATION OF FAST SHAPED-CHARGE JETS

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UDC 532.52

The effect of various methods for producing a fast shaped-charge jet on the jet velocity is studied. Experimental results allow one to optimize the process of formation of fast shaped-charge jets. Spectra of a copper jet are obtained, and its temperature is determined. It is shown that fast copper shaped-charge jets can be used for quasi-cw lasing.

Fast shaped-charge jets (FSCJ) have been the subject of just a few papers (see, e.g., [1–3]). An FSCJ is the stream of atoms and ions produced by explosive compression of a metallic cylindrical liner. A diagram of experiments on producing FSCJ is shown in Fig. 1. The liner is tightly connected to a glass tube from which air is evacuated. The pressure of the remaining air determines the maximum velocity of the jet. At a pressure higher than 1330 Pa, a jet is not formed. The maximum velocity of the jet is attained at a pressure of 10^{-4} Pa. This velocity can also be attained at higher pressure but it decreases as the jet propagates along the tube. It is established that the maximum velocity depends on the atomic weight of the liner material: the smaller the atomic weight, the higher the maximum velocity of the jet. The highest velocity is 90 km/sec for beryllium, 70 km/sec for copper, and 46 km/sec for lead. The liner is embedded in an explosive charge. Between the detonator and the liner there is an insert of an inert material, whose diameter determines the phase velocity of detonation-wave propagation along the liner and the maximum velocity of the FSCJ. An insert and charge of greater diameter are required to achieve a higher velocity. For copper, the maximum velocity was attained for a 20-cm-diameter charge. The jet velocity is also found to depend on the diameter and thickness of the liner walls. The density of the jet material is about 10^{-3} g/cm^3. A spectral analysis of a jet produced by compression of an aluminum liner showed that the jet consists of aluminum atoms and singly and doubly charged ions.

The object of the present work is to obtain additional experimental data on FSCJ to refine the region of application, in particular, data on the jet temperature, and to attain required velocities of FSCJ with as small explosive charges as possible.

In the present work, we studied primarily copper liners. Several experiments were performed using graphitic and aluminum liners. A diagram of the experiments is the same as in [1], i.e., a FSCJ propagated in a 37-mm-diameter tube from which air was evacuated to a pressure not higher than 10 Pa. For determination of the velocity of the jet head, markers 10 cm apart (in some experiments, 15 cm apart) were applied on the tube. The width of the markers was 1.5–2.0 cm. RDX of bulk density was used as the explosive. FSCJ were recorded by ultrahigh-speed photorecorder (USP), whose recording camera was used as a photochronograph. The rotation rate of the mirror was 60,000 rpm. A color film with a sensitivity of 400 ISO units was used.

Lavrent'ev Institute of Hydrodynamics, Siberian Division, Russian Academy of Sciences, Novosibirsk 630090. Translated from Prikladnaya Mekhanika i Tekhnicheskaya Fizika, Vol. 41, No. 5, pp. 62–67, September–October, 2000. Original article submitted December 4, 1998; revision submitted December 29, 1999.

 0021-8944/00/4105-0818 $25.00

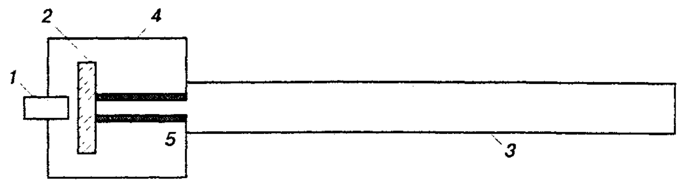

Fig. 1. Diagram of experiment on production of FSCJ: detonator (1), insert from an inert material (2), glass tube (3), explosive (4), and liner (5).

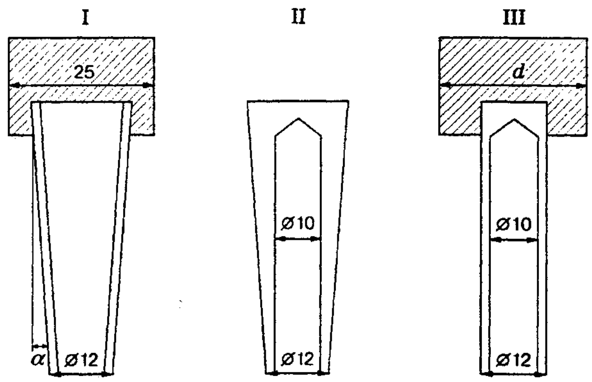

Fig. 2. Types of liners used in experiments.

In [1], it is established that for a given liner material, the jet velocity is higher the larger the charge diameter. The diameter of the inert insert is obviously proportional to the charge diameter. The presence of the inert insert leads to a decrease in the angle of approach of the detonation wave to the liner surface and to an increase in the phase velocity of detonation-wave propagation along the liner, and, hence, in the velocity of the point on the axis of the liner at which there is collision of the internal layers of the liner. This point will be referred to as the point of contact. It is clear that the higher the velocity of the point of contact, the higher the velocity with which the metal vapors are ejected from the liner. The velocity of the point of contact can be increased by several methods.

1. Use is made of an inert insert and liner I (Fig. 2) with diameter decreasing in the direction of detonation-wave propagation. The time required for the liner segments to reach the axis is longer for segments with larger diameter than for segments with smaller diameter. However, a detonation wave arrives at liner segments with larger diameter earlier. This allows one to obtain a small difference in the time of arrival of the initial and final segments of the liner to the axis, i.e., to attain the higher velocity of the point of contact.

2.Use is made of liner II (Fig. 2), whose wall thickness decreases in the direction of detonation-wave propagation. Segments with greater wall thickness are accelerated with lower velocity than segments with thinner walls, and for thicker-walled segments, the time required to reach the liner axis is longer. The detonation wave arrives earlier at liner segments with thicker walls, and this compensates for the lower velocity of the thick-walled segments. Because of this, as in the former case, it is possible to obtain a small difference in the time of arrival of the initial and final segments of the liner at the axis, i.e., the higher velocity of the point of contact.

3. Liner III (Fig. 2) was used for experiments in which the FSCJ velocity was increased by increasing the diameter of the insert of the inert material. This method of increasing the FSCJ velocity was used in [1–3].

The liner profiles presented in Fig. 2 are the simplest. They are used to develop the model since it is difficult to calculate the required profile exactly because the collapse process is influenced by the viscosity of the liner material and the viscosity for explosion conditions is not known.

TABLE 1

Experiment No.	Types of liner (Fig. 2)	α, deg	d, mm	v, km/sec
1	II	0	—	12
2	II	2	—	15
3	II	4	—	12
4	III	0	25	21
5	III	0	60	30
6	I	2	25	30
7	I	4	25	30

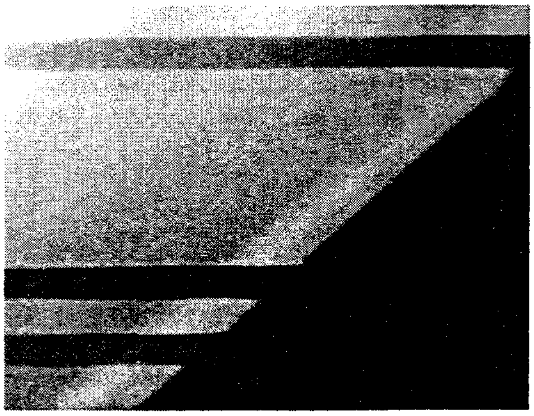

Fig. 3

Fig. 4

Fig. 3. Streak record of the jet head in experiment No. 5.

Fig. 4. Streak record of the jet head in experiment No. 7.

A number of experiments was performed with the liners shown in Fig. 2. In all cases, the liner length was 50 mm. In an experiment with an inert insert of 60-mm diameter, the charge diameter was 72 mm, and in all remaining cases, it was 37 mm. Table 1 lists values of the velocity of the FSCJ head v for some values of the diameter of the inert insert d and the slope of the generatrix to the liner axis α for various copper liners.

The results given in Table 1 indicates that by changing the liner shape it is possible to increase the jet velocity without increasing the charge diameter. In experiment Nos. 5–7, the velocity was the same although different charges were used. Figures 3 and 4 show that despite different methods for producing jets, the jet flow patterns were identical. For comparison, Fig. 5 shows a streak record of the jet head in experiment No. 1. The experiments indicate that the jet characteristics are nonuniform, but the nonuniformities in all cases are different in nature, and it is difficult to divide the jet into the penetrating jet and a FSCJ. The jet from liner II with an angle of 4° had much weaker brightness than the jet in experiment Nos. 1 and 2. A preliminary calculation for this liner shows that the velocity of the point of contact should decrease in the direction of propagation of the detonation wave.

As in [1, 2], the jet velocity depends on the liner material. In experiments with an aluminum liner having the same dimensions as in experiment No. 5, a velocity of 36 km/sec is attained.

Experiments were performed with graphitic liners. The charge diameter was 72 mm, and the diameter of the inert insert was 60 mm. Two cylindrical liners had outside diameters of 13 and 11 mm, inside diameters of 8 and 6 mm, and densities of 1.3 and 1.5 g/cm^3, respectively. Velocities of 27.1 and 14.6 km/sec, respectively were attained. Use of the same liners without an inert insert and with an explosive charge of 37-mm-diameter yielded a jet velocity of 10 km/sec. The density of ordinary graphite is equal to 1.9–2.1 g/cm^3.

Fig. 5. Streak record of the jet head in experiment No. 1.

Thus, because of the porosity of graphite, penetration of the detonation products of the explosive into the liner has a significant effect on the collapse process and leads to a decrease in the FSCJ velocity.

A number of experiments was performed to determine the temperature of FSCJ. Novikov [3] only give data on the temperature of FSCJ for impact on a target obtained by a pyrometric method. In contrast to [3], in the present work, the temperature was determined by a spectral method and the jet flow around a thin wire was studied experimentally. Experiments on the flow around the wire were performed before spectra were taken to obtain tentative temperature estimates. The jet temperature was determined before impact on a target. In the experiments described below, we studied jets produced from a copper liner with an outside diameter of 12 mm and inside diameter of 10 mm without an inert insert. The liners are embedded in an RDX charge of 37-mm diameter. In a gas-dynamic experiment, a thin steel wire was placed at 50 mm from the liner along the paths of the jet. It was assumed that in flow a shock wave would arise and a photo would show the wedge formed by the shock-wave front. Since the jet velocity is known (12 km/sec), by measuring the cone angle of the wedge, it is possible to determine the shock-wave velocity. Photography was performed using an USP whose recording camera was used as "time lense." A photograph of a wedge with an apex angle of 16°. Thus, the shock-wave velocity (1.67 km/sec) is determined. We assume that shock wave propagates with the velocity of sound and copper vapor is an ideal gas with an adiabatic exponent of 5/3. Hence we found that the jet temperature is 12 700 K. Since the shock wave propagates with a velocity that is obviously higher than the velocity of sound, the value obtained is higher than the real temperature of the jet and is an upper bound.

Using an ISP-51 prism spectrograph, we obtained a spectrum of a copper FSCJ, similar to the spectrum of a copper arc, on which the continuous spectrum of the main jet and detonation products flying past the FSCJ is superimposed. In order for the continuous spectrum to be separated from the spectrum of the FSCJ, the radiation of the spectrograph was recorded by the USP camera. To obtain a time sweep of the spectrum, it is necessary that the spectral lines be directed perpendicular to the rotation axis of the USP. The spectrum was rotated through 90° by a prism placed between the spectrograph and the USP [4]. The spectrum of the jet was taken on a Kodak film with a sensitivity of 3200 ISO units, which was increased to 6400 ISO units during development using a D-76 developer. The jet temperature was determined from data of measurements of the relative intensities of spectral lines. The accuracy of the method depends on the choice of lines. We used the tested set of lines of copper proposed in [5]. The recording camera of the USP recorded lines with wavelengths of 510.6, 515.3, 521.8, and 522.0 nm. The last two lines merged because of the insufficient resolution of the spectrograph.

A time sweep of the spectrum is shown in Fig. 6. Three experiments were performed. Different values of temperature were obtained for different pairs of lines. For example, for lines with wavelengths of 510.6 and 515.3 nm, the calculated temperature was 5500 K, and for the pair of 510.6 and 522.0 nm, the

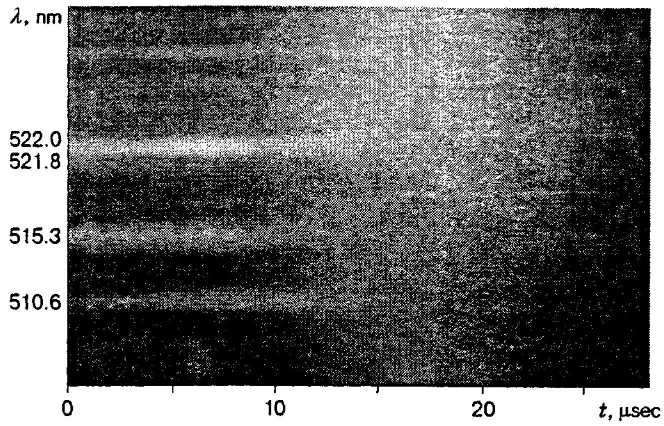

Fig. 6. Time sweep of the spectrum of a copper FSCJ.

temperature is 6600 K. It is possible that the two different values of temperature are due to departure from thermodynamic equilibrium in the expanding jet. The jet is cooled during expansion, and during relaxation, the level populations can differ from the equilibrium populations. The method of relative intensities is based on the fact that the energy distribution of the atoms is the Boltzmann distribution. Averaging data of three experiments, we find that the temperature of electrons in the jet is equal to 6000 K.

FSCJ can be used for quasi-cw laser operation. Most gas lasers are pulsed because generation leads to an increase in the population of the lower operating level and inversion disappears. A copper vapor laser is one of the most widely used and effective lasers. The lower operating level of the copper laser is metastable, and, up to now, it has not been possible to implement fast depletion of this level for maintenance of continuous generation. There is, however, the fundamental possibility of maintaining cw lasing by rapidly changing the medium in the operating laser zone using a gas stream. For this, the atoms that passed from the upper to the lower operating level should be rapidly removed from the generation zone. Let us estimate the gas-stream speed required for continuous operation of a copper laser. It is known that the pulse duration cannot exceed 0.1 μsec, which is explained by the lifetime of the upper laser level. The width of the active region should be not smaller than 1 mm since in a narrower zone, it is difficult to implement pumping of the active medium. To eliminate the gas from a strip 1 mm wide for 100 nsec, the gas-stream speed must be not lower than 10 km/sec. The minimum speed of a copper FSCJ is 12 km/sec. Thus, the FSCJ speed is sufficient for quasi-cw lasing. In this case, the ratio of the concentration of copper atoms at the metastable level to the total copper concentration should not exceed 0.06, which corresponds to an electron temperature of 3500 K; otherwise, the metastable level is populated to such an extent that generation is impossible [6]. Since the measured temperature is higher than the required value, further cooling of the jet by expansion is necessary. Buchanov et al. [6] examined this problem theoretically as applied to the jet from a plasma accelerator and showed that at an initial temperature of 11,000 K in the presence of a buffer gas, the jet can be cooled to the necessary parameters by expansion.

The results obtained lead to the following conclusions.

1. The process of producing FSCJ can be optimized by an appropriate choice of the liner shape. In particular, when using a conical liner in combination with an inert insert, to attain a velocity of 30 km/sec, one needs an amount of explosive 4 times smaller than that using a cylindrical liner.

2. At the exit from a copper liner, the temperature of a copper FSCJ is below 6000 K.

The author is grateful to Yu. A. Trishin for his attention to the work.

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