Electric discharge generator of long-lived plasma formations in atmospheric pressure air

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Abstract. The paper presents the results of a study of the developed pulsed plasma generator based on the cylindrical foil electric explosion. The generator is used to form large-scale toroidal plasma vortices in atmospheric air. The influence of the specific stored energy on the phase composition of the plasma flow and the lifetime of plasmoids using a high-speed camera was studied. It was found that large condensed particles in the flow do not participate in the vortex motion and cause the destruction of plasma vortices. The formation conditions of stable plasma vortices were determined.

1. Introduction
Long-lived formations are toroidal plasma vortices formed by pulsed injection of a supersonic plasma jets into atmospheric air. Its afterglow time is several orders of magnitude longer than the energy deposition time. Studies of this plasma structures are of significant scientific and practical interest for solving the problems of creating a powerful radiation source [1-3], a laboratory analogue of ball lightning [4], attenuation of shock waves during interaction with plasma [5]. The generation of plasma vortices is a complex and multifactorial process, that depends on the gas-dynamic characteristics of the plasma jet, its phase composition, etc. Formation conditions of vortex rings on plasma generators operating on gaseous plasma-forming materials are described in [6]. The use of metals as plasma-forming materials [1, 7] is of particular interest, which makes it possible to achieve a high efficiency of stored energy conversion into radiation. Under these conditions, the plasma flow contains a condensed phase, that affects the main characteristics of vortices, in particular, their stability, afterglow time, optical characteristics etc. [8, 9]. In the research [1] the plasma vortices were produced in less than half of the cases of discharge pulses. The causes leading to the instability of vortex generation process and the issues of their further stability were not considered in detail. However, it is important for solving the light source design problems. This work is aimed at studying operating modes of the experimental generator and the processes causing the stable transformation of the plasma flow into a vortex ring.

2. Experimental
We designed a pulsed plasma generator based on a localized electrical explosion of the cylindrical foil. The plasma generator (figure 1a) is formed by a flexible dielectric (polyvinyl chloride) channel (Ø10 x 35 mm) and two electrodes, one of which is made in the form of a nozzle. The use of a flexible dielectric channel wall supported by a metal shell makes it possible to achieve high strength of the generator. A metal cylindrical foil is installed in the channel before each experimental shot. The plasma generator is powered by a capacitative storage $C = 962 \, \mu F$. The operating voltage $U_0$ of the battery is 1–5 kV.
Figure 1. Electric discharge generator of heterogeneous plasma

(a) schematic diagram: 1 – elastic dielectric (PVC); 2 – shell; 3 – rod cathode; 4 – anode-nozzle; 5 – dielectric; 6 – plasma-forming insert; (b) appearance.

A pulsed jet is formed when the installed in the channel foil is electrically exploded. The generator produces a heterogeneous plasma flow, and its phase composition is controlled by changing the mass of the plasma-forming material and the input energy. In this study we varied the value of the specific stored energy per unit mass of the plasma-forming substance \( q = W_0/m \) (\( W_0 \) is the energy stored in the capacitor bank, \( m \) is the mass of the plasma-forming material). Aluminum was used as plasma forming material.

The electrical characteristics were recorded using a Pearson 4418 current sensor and an AKTAKOM ASA 6039 high voltage divider. Registration of the vortex ring formation process, determination of the vortex ring lifetime (afterglow duration) and visual analysis of the flow composition were carried out using a Casio EX-F1 9 high-speed camera (600 fps).

3. Results

Figure 2 shows typical frames of the process of formation of plasma-vortex rings at various values of \( q \). The obtained frames showed that for different values of \( q \), three main modes of vortex formation are realized: unstable, partial stability and stable modes. For unstable mode (figure 2a) plasma jet transforms in an asymmetric fast-breaking structure and vortex ring is not produced.

The partial stability mode (figure 2b) is characterized by the destruction of the vortex ring by condensed particles in the flow. A plasma toroidal vortex in the regime of stable formation is an azimuthally homogeneous structure with a lifetime of more than 13 ms (figure 2c).

The figure 3a shows the data for the lifetime of the plasma vortex, obtained from the processing of high-speed video recording. Filled dots correspond to cases of stable and partial stable vortex formation modes, unfilled dots correspond to unstable one. The most stable plasma vortices are produced at \( q = 20 \ldots 30 \) kJ/g and foil masses of 150 mg and 200 mg. The mode of unstable formation is typical for foil masses less than 100 mg, and partially stable - for masses of more than 200 mg.

An analysis of the electrical characteristics showed that in all the cases a subcritical damping regime with two current half-waves is realized (the damping parameter \( \gamma = 0.73 \), the duration of the first half-cycle is \( T_{1/2} \sim 90 \) \( \mu \)s), and the electric explosion occurs without a current quasi-pause. During an electric explosion, the input energy is spent on the phase changes of the conductor, its dispersion, the formation of liquid and vapor phases (\( W_{\text{expl}} \)). Further heating and expansion of the products of the electric explosion by a high-current discharge (\( W_{\text{pl}} \)). Variation of \( q \) in these studies led both to a change in the ratio between the explosion and plasma energies and to a change in the total efficiency of the energy input (figure 3b).

In the graphs on the second abscissa scale the \( q \) values are normalized to the aluminum sublimation energy \( Q_{\text{subl}} = 11.4 \) kJ/g.
Figure 2. Typical frames of plasma vortex rings formation: (a) unstable formation ($q=35-120$ kJ/g); (b) partially stable ($q=8-15$ kJ/g); (c) stable ($q=20-30$ kJ/g).

With the mass of the plasma-forming foil $m=250$ mg and $q=8\ldots20$ kJ/g ($0.7\ldots1.8$ $Q_{\text{subl}}$), the overall efficiency of the energy input and the energy spent on heating and accelerating the plasma flow are reduced. In this mode the electric explosion occurs after the discharge current maximum, and a large number of large drops are observed in the flow, which are not involved in the vortex motion and disrupt the vortex formation process (figure 2b).

![Figure 3. The dependence of the lifetime (a) and the efficiency of energy transfer to the load (b) on the specific energy input $q$.](image)

The specific energy spent on the explosion $W_{\text{expl}}/W_0$ decreases with the growth of $q$ (decrease in $m$), thus the efficiency of metal destruction decreases. The specific energy spent on heating and accelerating the plasma $W_{\text{pl}}/W_0$ increases and the amount of the liquid phase in the flow decreases as well. The electric
explosion time decreases and is similar to the discharge current maximum time at \( q=20-30 \) kJ/g (\(-1.8-2.6 \ Q_{\text{subl}}\)).

Figure 4 shows the electrical characteristics of one mode, in which the electric explosion occurs near the current maximum and the vortex formation is formed stable (\( q=30 \) kJ/g).

![Figure 4](image)

**Figure 4.** Electrical characteristics of the generator at \( U_0=3.0 \) kV; \( W_0=4.3 \) kJ; \( m=150 \) mg (\( q=30 \) kJ/g): (a) current and generator voltage; (b) electrical power and energy.

The maximum current is reached at \(~40 \) µs and is 65 kA. The total energy release time is \(~100 \) µs, the peak voltage on the generator exceeds 2.5 kV, the peak electric power is \(~165 \) MW, \( W_{\text{int}} \sim 3.3 \) kJ is transferred to the load (\( W_{\text{int}}/W_0 \sim 76\% \)). The energy consumption for the explosion is \( W_{\text{expl}} \sim 1 \) kJ, the efficiency of the energy input into the plasma is \(~53\% \) of the stored energy (\( W_{\text{pl}} \sim 2.3 \) kJ).

With a further increase in \( q \) more than 30 kJ/g (\( >2.6 \ Q_{\text{subl}} \)) the total efficiency of energy transfer to the load decreases as well as the density of the outflow and the formed plasma structure (figure 2a), despite a significant decrease in the droplet phase fraction in the flow and a high efficiency of energy transfer to plasma.

4. Conclusions

The modes of operation of a pulsed electric-discharge generator of heterogeneous aluminum plasma were studied in a wide range of values of the specific stored energy (from 0.7 to 10 sublimation energies of the plasma-forming material). The specific stored energy influence on the characteristics of electroexplosive processes, which cause the transformation of a plasma flow into radiating vortex structures, has been found. An empirical ratio for stable vortex generation has been obtained (\( q=20...30 \) kJ/g). If the electric explosion occurs near the current maximum, then the plasma jet contains the optimal number of drops involved in the vortex motion, and the jet transforms into a stable vortex. Deviation from the ratio leads to an increase in the proportion of a large droplet phase, which is not involved in the vortex motion and destroys the vortex ring. A critical decrease in the mass and density of the formed plasma jet leads to the rapid destruction of the vortex structure.

Acknowledgments

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