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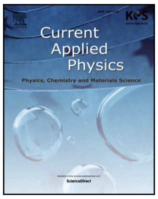

Modeling of the initial stages of the formation of heterogeneous plasma flows in the electric explosion of conductors

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ABSTRACT

The experimental and theoretical studies on scattering of electric explosion products in the end-type plasma accelerator are carried out. Using the method of high-speed imaging (10^6 shots per second), it is revealed that there are three zones in a heterogeneous plasma flow. Zone 1 is a plasma focus, in Zone 2 there is a 90° turn of a flow, whereas a plasma flow is parallel to the dielectric disk in Zone 3. Following the concepts of plasma scattering when exposed to magnetic and gas-dynamic pressure, a mathematical model is proposed and provides an adequate explanation of plasma motion in Zone 3. It comprises equations of laws of mass and conservation of momentum, as well as the first and second Kirchhoff's laws. The outcomes of modeling are in compliance with the experimental data. A numerical single-fluid magnetohydrodynamic model is developed for general description of formation and evolution of a plasma flow. It is based on Navier-Stokes and Maxwell's equations. The obtained patterns of plasma current distribution agree satisfactory with the results of high-speed imaging. They point at a jet in the central part of the electrode, which splits out with the distance from its surface.

1. Introduction

In recent years, the electric explosion of conductors has been in the focus of researchers because of its importance for a wide range of scientific and industrial processes. To date, a complicated nature of this phenomenon has been revealed in significant theoretical works and in numerous experiments [1–8]. The electric explosion of conductors can result in such processes as discharge of electricity and formation of metallic plasma, a plasma spread under thermal and magnetic pressure; plasma acceleration of explosion products, formation of a heterogeneous plasma flux and its reaction with the target surface. Several ways to supply power to a conductor are available, a front coaxial electrical explosion of conductors is one of them, i.e. electrodes are in a coaxial position and a conductor to be exploded (a round foil or a stripe) closes these electrodes [9]. This geometry of electrodes has been used to form plasma fluxes for hardening and destructing of materials [10,11]. Formation of heterogeneous plasma fluxes (HPF) is one of the most significant processes. This process influences directly distribution of alloying elements in the surface layers of a treated product, and quality of the formed coating as well. Despite importance of these processes they have been hardly analyzed for HPF so far. However, some detailed research is available for other fields: plasma accelerators [12,13], formation of stable current-carrying conductors [14], Artzimovich Plasmatron [15], Marshall's gun (rail gun) [16], and plasma focus [17–21].

Theoretical studies on processes taking place in plasma accelerators have revealed a complex of hydrodynamic, thermal and electromagnetic phenomena; therefore, mathematical modeling necessitates the use of an equation system for time-dependent magnetic and gas dynamics of emitting plasma. Since these equations are complicated, their system can be solved numerically only, providing a detailed description of plasma focus formation. A further study is needed to formulate and solve this problem numerically. On the other hand, various significant assumptions are made in the available numerical models of accelerators, so integral parameters of plasma fluxes might be distorted to a certain degree. As a consequence, definite procedures and models are used when modeling plasma fluxes, which simplify the initial system of equations and enable considering simultaneously parameters of the unit with characteristics of plasma fluxes. Such models are classified as the first-level models in Refs. [15,18], e.g. models of a disk and a snow fighter. The second-level models describe phenomena in plasma according to magnetic hydrodynamics and special equations of state. To date, researchers have been improving the available models [20,21] via their generalizing to a 3D case.

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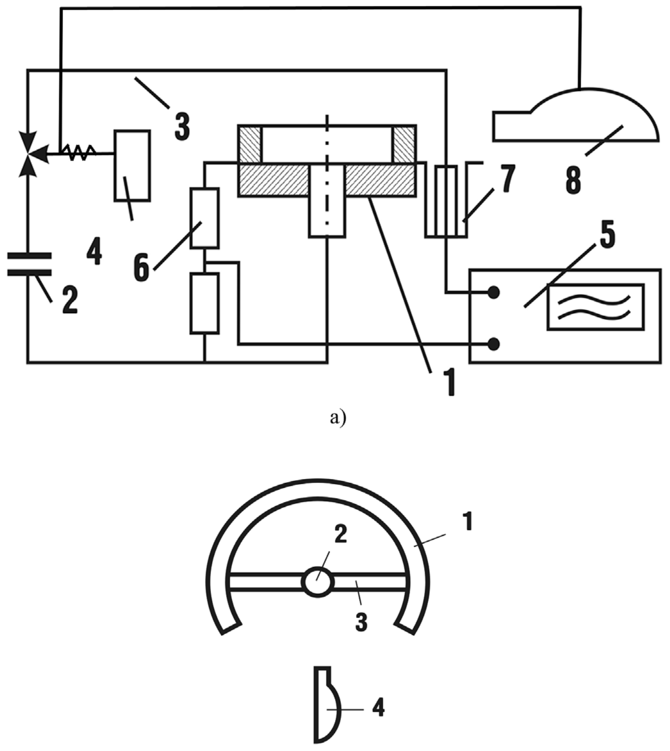

a)

b)

Fig. 1. Layout of the unit (a) and photo registration (b). a) 1 – plasma accelerator; 2 – condenser battery; 3 – prevacuum discharger; 4 – igniter; 5 – storage oscilloscope; 6 – voltage divider; 7 – coaxial shunt; 8 – ultra-high-speed photo recorder. b) 1 – hold-down ring; 2 – central electrode; 3 – exploding stripe; 4 – ultra-high-speed photo recorder.

This work aims at finding out how heterogeneous fluxes of plasma are formed in the front plasma accelerator with electrodes positioned coaxially. In the furtherance of this goal it is necessary to determine phases in formation of heterogeneous plasma fluxes using the methods of high-speed imaging; develop a simplified model of plasma spread, and evaluate numerically a magnetohydrodynamic plasma flow.

2. Material and methods of experiment

It is necessary to know phases in formation of a heterogeneous plasma flux in order to obtain initial data for a mathematical model. High-speed imaging in the optical band is the most informative experimental method of research into formation and distribution of plasma fluxes. A basic optical scheme of the unit including an ultra-high-speed photo recorder with reporting of the process, and a discharger capable to synchronize the beginning of a spread and imaging are shown in Fig. 1. The pattern of a spread was shot perpendicular to the accelerator axis through the opening in a hold-down ring (Fig. 1 b). The eye shot was 60 x 60 mm^2. In the experiments [10,11,22] ultra-high-speed imaging was carried out when plasma was ejected through the nozzle or hold-down disk. It was not possible to register when a flux began to form. The reported procedure differs from the known ones because it enables observation of the plasma spread from the initial moment of discharge formation. It is mainly possible due to stripe-shaped foils hold down by a split ring (Fig. 1 b), which were used in our experiments alongside with round foils hold down on the edges by a ring, the thickness of which limited the eye shot. The developed procedure makes it possible to follow the process of plasma spread from the beginning of discharge formation. To eliminate electrical interferences a copper cylindrical shell with a thickness of 0.9 mm was made to connect a lid of the closing device with the body structure. The resistance of a shell section, where voltage was measured, was 4.4·10^{-7} Ohm. The alteration of voltage vs. time dependence was registered by a storage oscilloscope. The absolute value of electrical current was calculated via dividing voltage by resistance of a shell section. In case of a shortcut in the first semi-period the dependence of current strength on time is a sinusoidal function, a sharp drop in the maximal amplitude is observed at the beginning of the second semi-period due to an abrupt change in the resistance of a prevacuum discharger (Fig. 2). The second fact is proved by the dependence of current derivative vs. time measured by a Rogovsky belt; this dependence has a sharp rise when passing into the second semi-period. Under a shortcut of the discharging circuit the main resistance, being negligible in the first semi-period ($R = 10^{-7}$ Ohm), is concentrated in the prevacuum discharger. Taking into consideration this fact and using the formulae of an optimum oscillating circuit, parameters of the unit were estimated: capacity C = 2.7 mF, inductance L = 0.084 μH, and a semi-period of the discharge $T_{1/2} = 47 \pm 1.5$ μs. Provided that capacity and inductance of one condenser: $C_0 = 150$ μF, $L_0 = 600$ nH, inductance of the battery 30 nH and supplying buses 54.7 nH can be determined. The obtained data are relevant for calculating parameters of the mathematical model. The maximal values of electrical current are 170 kA and 85 kA. This difference is possible because some electrical current is ejected from the discharge area in the form of a plasma focus.

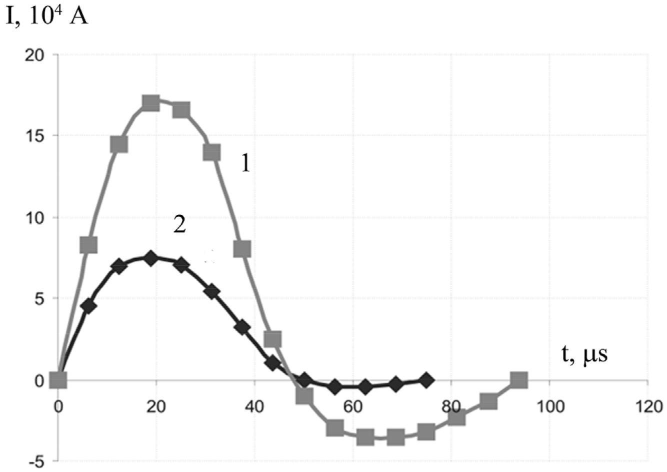

Fig. 2. Current strength vs. time (oscillographs (bandwidth 700 MHz)). 1 – shortcut; 2 – spark discharge through plasma.

3. Experimental results and discussion

Fig. 3 shows images made in high-speed imaging. As seen, a zone expanding spherically is formed nearby the central electrode at the reference time (up to 10 μs), and simultaneously a discharge occurs between electrodes. At t ≥ 10 μs a quasi-stationary configuration with a jet in the center is formed, the base of it is parallel to a dielectric disk. Three typical zones in formation of a flux were revealed with the help of imaging (Fig. 4 a). The flow is parallel to the axis in the first zone. A 90-degree turn takes place in the second zone. The lines of electric current are parallel to the dielectric disk in the third zone. In accordance with the obtained data plasma is considered as a structure comprising two specific zones: a high-speed jet – plasma focus with a low density and a high density disk with a low velocity. Therefore, motion of plasma in the first and third zone is relevant for the development of a mathematical model.

3.1. A model to describe formation of heterogeneous plasma fluxes

We consider a simplified problem of flux motion and discharge for a front accelerator. For this purpose the dynamics of zone around the