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Near-cathode plasma and gas-dynamic processes during the formation of a spark discharge in air at atmospheric pressure in the gap point–plane

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Received December 2, 2022
Revised February 3, 2023
Accepted February 4, 2023

Using the method of shadow photographing, the formation of a spark discharge in the „tip (cathode)–plane" interval with a length of 1.5 mm is investigated. Two types of shock waves have been registered cylindrical, created when the discharge channel expands, and cathode, presumably generated by cathode flares near the surface of the tip electrode. The computational and theoretical consideration of the proposed mechanism is carried out.

Keywords: gas discharge, microstructure, electron temperature, degree of gas ionization.

DOI: 10.21883/TPL.2023.04.55876.19448

Since pulse high-voltage atmospheric-pressure discharges are used widely in practice, they have been studied extensively for a long time. Such discharges are characterized by distinct gas dynamics, which may evolve over nanosecond timescales and may be examined using shadow techniques (see [1–10] and references therein).

The first studies [1–4] revealed the structure of a spark discharge with a high-conductivity channel, a transitional region, and a radially expanding (cylindrical) shock wave (SW).

Using laser probing and interference techniques, the authors of more recent papers [5–10] examined a spark discharge in the point–plane geometry in air and found that its microstructure features a multitude of microchannels. Additional studies of gas dynamics were also performed: the dynamics of formation of the above-mentioned radial structure of the discharge channel was detailed [7,8], and hemispherical SWs with their sources located on the surface of a planar electrode were detected [6].

A single-frame shadow photography technique was used in [5–8]. This limited the potential to examine the dynamics of gas-discharge processes. The aim of the present study is to obtain new data on gas-dynamic and plasma processes associated with a spark discharge in atmospheric-pressure air using double-frame shadow imaging.

The experimental procedure for the point–plane discharge geometry in atmospheric-pressure air and the experimental equipment were discussed in detail in [5–8,11]. A negative pulse with an amplitude of 25 kV and a duration of 7 ns was applied to the discharge gap via a 7-m-long cable. The pointed axially symmetric stainless-steel electrode had the following parameters: a length of 19 mm, a diameter of 14 mm, an apex angle of 36°, and a curvature radius of 0.15 mm.

The measurement system included a dual-channel optical discharge detection system with a source of probing radiation (solid-state laser with a wavelength of 532 nm and a half-amplitude pulse duration of 6 ns [11]), which made it possible to record two frames per pulse with a time interval of 5 ns. The spatial resolving power of the optical system was 5 μm per three pixels. The exposure for each frame was set by the laser pulse duration. Frames were timed relative to the moment of breakdown.

Figure 1 shows two shadow patterns for a discharge recorded in a single pulse. The obtained results agree with earlier data [5–8] on the formation of a microchannel structure and a cylindrical shock wave and the radial expansion of a high-conductivity channel. In addition, the shadow patterns reveal new structural elements in the vicinity of the pointed electrode surface: narrow (with a thickness no greater than 15 μm) bright regions extending from the cathode surface. Experimental data suggest that such structures are detected 10–50 ns after breakdown and propagate with a velocity of 1–3 km/s. Judging by their appearance and the above velocity value, these regions are likely to be shock waves propagating from the cathode. In most cases, their shape corresponds to the cathode surface profile. These SWs are hereinafter referred to as near-cathode ones.

It needs to be emphasized that the near-cathode SW front often had a substantial length (up to 0.3 mm). Apparently, this pattern corresponds to a distributed SW source on the cathode surface or a large ensemble of synchronized sources.

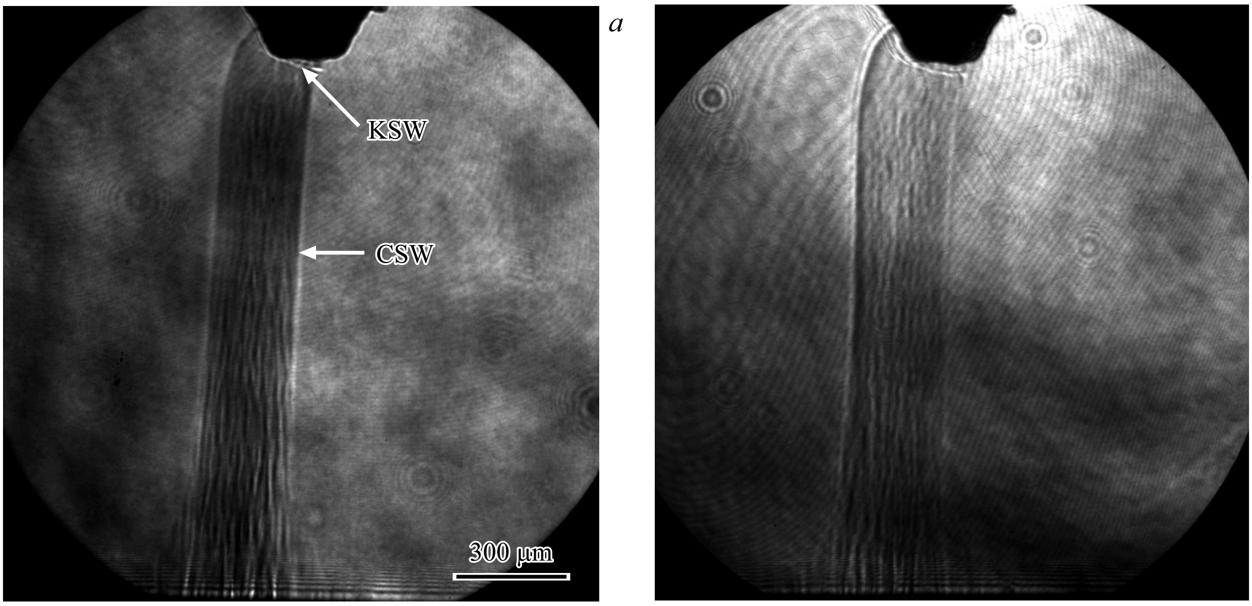

Figure 1. Shadow patterns obtained in a single pulse. *a* — The first frame, 20 ns after breakdown; *b* — the second frame, 25 ns after breakdown. KSW and CSW are near-cathode and cylindrical shock waves, respectively. The pointed cathode is at the top.

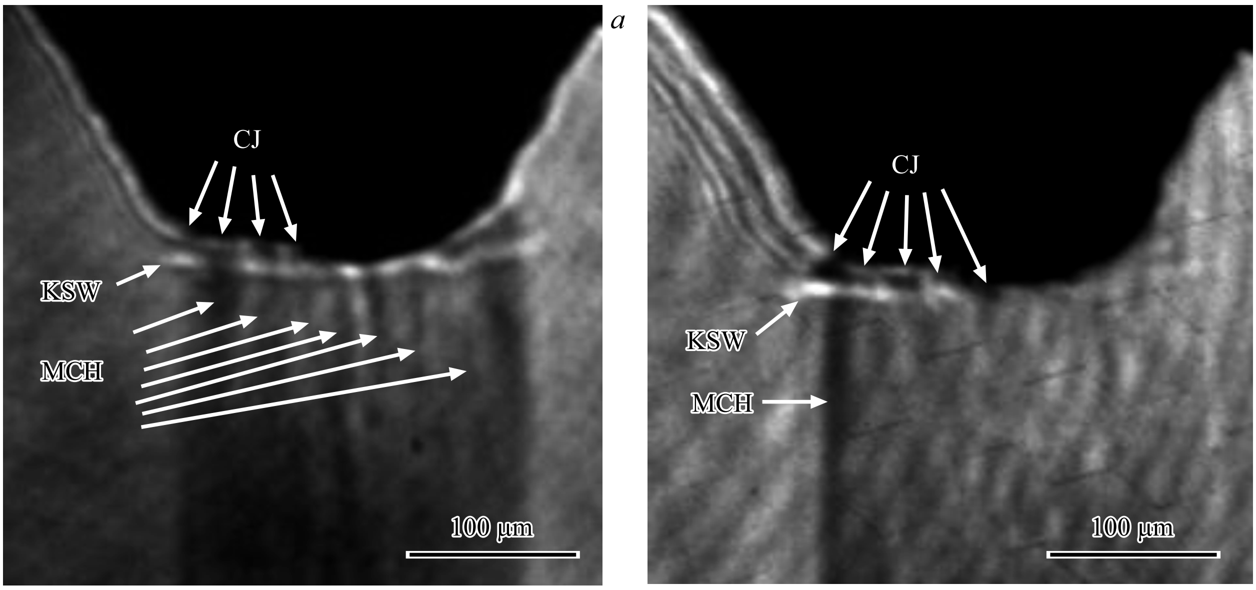

Figure 2. Enlarged shadow patterns. *a* — The first frame, 18 ns after breakdown; *b* — the second frame, 23 ns after breakdown. CJ and MCH are cathode flares and microchannels, respectively.

The obtained data (Fig. 2) suggest that individual regions of the SW front are produced by cathode flares. The cathode plasma expansion rate was estimated at $1-2$ km/s, and the width of flares was $10-15\,\mu$m. Flare regions were associated with microchannels with similar diameters.

Note that the shadow patterns recorded in [9] under similar experimental conditions also revealed the formation of local plasma flares from electrode spots (on both pointed and planar electrodes) with a size of approximately $30\,\mu$m. This process commenced 0.5 ns after breakdown. However, the observation of near-electrode SWs was not reported in [9]. In the present case, no cathode flares and associated SWs were observed less than 10 ns after breakdown.

Let us examine the possibility of generation of the observed near-cathode SWs due to the motion of flares formed by a vaporized cathode material. Assuming that a flare is greater in size than the region out of which the material was ejected, we write the following for its expansion rate in the adiabatic approximation [12]:

$$v = \sqrt{\frac{4\gamma}{(\gamma-1)m_i}(\varepsilon_{i0} + Z\varepsilon_{e0})}, \qquad (1)$$

where ε_{i0} and ε_{e0} are the initial energies of ions and electrons, $\gamma = 5/3$ is the adiabatic constant (expansion of a monoatomic gas is considered), m_i is the ion mass, and Z is the ion charge. The electron energy is assumed to be equal to the Fermi energy [12], which is related to the electron concentration as $\varepsilon_{e0} \sim n_e^{2/3}$. For definiteness, the initial ion energy is taken equal to the boiling point of iron $\varepsilon_{i0} = 0.27\,\text{eV}$ [13]. Assuming that the initial degree of ionization of metal vapor satisfies condition $Z\varepsilon_{e0} \ll \varepsilon_{i0}$, which corresponds to electron concentration $n_{e0} < 10^{20}\,\text{cm}^{-3}$, we derive the following from Eq. (1): $\upsilon = \sqrt{\frac{4\gamma\varepsilon_{i0}}{(\gamma-1)m_i}} \approx 2\,\text{km/s}$. This agrees with the experimental values.

Note that if full ionization (and, possibly, multiple ionization) of metal vapor in a flare is assumed, the Fermi energy has a dominant role in Eq. (1), and velocities at the level of $\upsilon \approx 20{-}30\,\text{km/s}$ are obtained. Such values were observed in a number of experiments (see [12] and references therein).

Next, we assume that a cathode flare produces a strong SW, which gets detached from a flare and propagates in unperturbed gas (in the present case, in air). The temperature at the SW front may then be estimated as [14]

$$\frac{T}{T_0} = \frac{2\gamma(\gamma-1)}{(\gamma+1)^2}M^2,$$

where T_0 is the temperature of unperturbed gas and $M = V/c$ is the Mach number. The temperature of gas beyond an SW front corresponding to average SW velocity $V = 2\,\text{km/s}$, speed of sound in air $c = 345\,\text{m/s}$ (at air temperature $T_0 = 300\,\text{K}$), and $\gamma = 1.3$ (needed to take the excitation of vibrational levels into account) is estimated at 1500 K. Note that the obtained value is close to the gas temperature in microchannels [15].

Thus, the presented results reveal a third type of shock waves that accompanies a spark discharge and exists alongside with cylindrical and hemispherical SWs: a near-cathode SW, which is presumably generated by cathode flares near the surface of a pointed electrode.

Funding

This study was supported financially by the Russian Foundation for Basic Research (grant No. 20-08-01069A).

Conflict of interest

The authors declare that they have no conflict of interest.

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