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Electrophysical and thermal parameters of the atmospheric pressure plasma jet in helium excited by sinusoidal and pulsed voltages

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Comparative studies of cold plasma jet of generation at atmospheric pressure in helium excited by sinusoidal and unipolar positive pulses voltage at 2−6 kV for medical applications were carried out. It has been shown that the achieved parameters are identical, but the absence of the effect of frequency self-organization of streamer breakdown leading to irregularity in streamer propagation under pulse excitation makes it preferable in biophysical experiments. A limiting factor for plasma jet exposure is the achievable target temperature, which can be reduced by limiting the current duration.

Keywords: cold plasma jet, excitation by sinusoidal and pulsed voltage, temperature.

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Interest in plasma generation at atmospheric pressure (in particular, cold discharge, which under certain conditions goes beyond the disharge region, forming what in modern terminology is called a cold plasma jet (CPJ) stems from its applications in plasma medicine [1–5]).

The influence of plasma formations on biological objects facilitates chemical reactions in the gas phase and liquid at the plasma−biological object interface [2–4,6]. The nonequilibrium nature of plasma provides an opportunity to produce chemically active substances without excessive heating of the gas and affect targets (live organisms included) that are sensitive to heating. Currently, the effects of CPJ on biological objects is one of the approaches providing activation of viability suppression processes of cancer cells with different histological origin.

CPJ sources operated by applying sinusoidal voltage to electrodes are commonly used in biophysical experiments. Streamers initiated within each positive voltage half-wave propagate in a flow of inert gas into the environment and form a plasma jet. The effect of frequency self-organization of streamer breakdown was discovered in [8] in experiments with a dielectric target subjected to a CPJ. Frequency f_I of current pulses detected near the target depends on amplitude U and frequency f_0 of the applied sinusoidal voltage, distance z from a nozzle to the target, and the target type and deviates from f_0. This effect is subject to the conditions in the nozzle−target gap and is governed by the relation between the plasma density in a streamer head and the residual plasma density above the target surface. All electromagnetic and chemical processes near the target depend on the frequency of plasma–target contacts. The unregulated process of changing the parameters of CPJ leads to uncontrollable and often unreproducible conditions of exposure to the target, can induce local overheating of living tissues due to an increase in temperature of the plasma-forming gas and lead to destabilization of cellular proteins. For in vitro and in vivo applications of CPJ, its parameters must be monitored to ensure that it is effective and safe when exposed to living tissue.

The purpose of this research is to compare the parameters of the CPJ influence on target (current, frequency dependences, target temperature, spectral composition of the jet above the target surface) when excited by sinusoidal and unipolar positive pulses voltage as applied to biophysical studies.

A sinusoidal voltage generator operated at fixed frequencies $f_0 \approx 13$, 21, 52 kHz and a generator of unipolar positive pulses with adjustable repetition frequency $f = 3-30$ kHz were used to produce a CPJ. Voltage amplitude U remained within the 2−6 kV range in both cases and was limited to ensure safety of CPJ treatment of living objects.

The CPJ source was a coaxial dielectric channel 100 mm in length with an inner diameter of 8 mm and a nozzle (in the form of a capillary 2.3 mm in diameter) at its end [8–10]. The discharge zone was formed by two electrodes. The excitation voltage was applied to an inner rod electrode 50 mm in length and 2 mm in diameter, which was positioned at the center of a channel, relative to a circular grounded electrode located outside of the channel. Voltage U was measured with a high-resistance divider. A metallic collector electrode (copper substrate) was positioned at distance $z = 20$ mm from the nozzle perpendicular to the CPJ propagation axis. The value of z was chosen so as to match the typical conditions of experiments on CPJ treatment of culture media and experimental animals. Grounding the collector through a low-inductance resistor made it possible to register a current pulse I reaching the substrate.

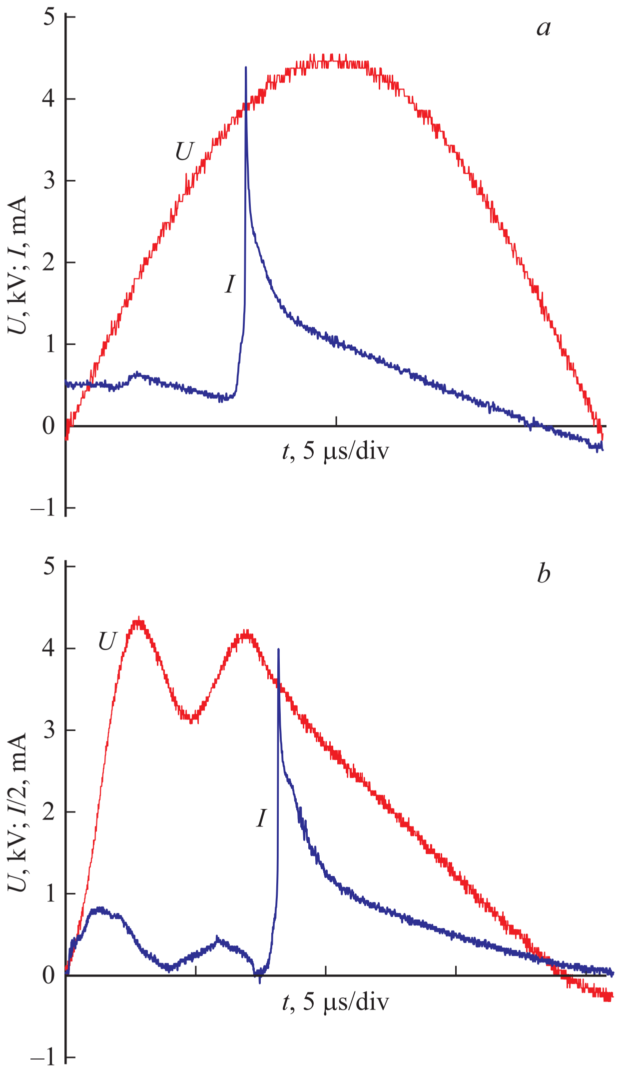

Figure 1. Oscillograms records of voltage U at the high-voltage electrode and collector current I under excitation by sinusoidal (a) and pulsed (b) voltage. $f_0 \approx f \approx 13$ kHz.

Another reason to use this substrate stems from the fact that an elevated-intensity electric field is established in the plasma streamer–grounded electrode gap. Combined with an increase in the amplitude and the frequency of excitation voltage, this intensifies the generation of active radicals in the region of CPJ–target contact. An auxiliary additional grounded electrode is positioned for this purpose below the tray with objects in biological experiments [4,9,10].

When the working gas (helium of grade A with purity of 99.995%) was pumped through the channel at a flow rate $v > 1$ l/min and when either a sinusoidal voltage with $U \approx 0.7$ kV or unipolar positive pulses with $U \approx 1.1$ kV were applied to the electrodes, a discharge was ignited in the discharge gap. At exceeding $U > 1$ kV and $U > 1.5$ kV, respectively, a plasma jet was formed, exiting the channel crossed. The spatial localization of a plasma formation depends on the channel geometry, capillary size, flow rate, and voltage. The jet length reached 70 mm under the optimum conditions at $U = 3-5$ kV and $v = 5-10$ l/min.

The oscillograms records of voltage and collector current for both excitation types at $U \approx 4.5$ kV, $f_0 \approx f \approx 13$ kHz are presented in Figs. 1, a, b. Experiments demonstrate that the current at the target is complex in nature and features fast (streamer with a duration up to 100 ns) and slow (with a duration of 5–10 μs) parts.

Figure 2, a presents dependences $I(U)$ of the collector current amplitude on the applied voltage amplitude for various gas flow rate under sinusoidal and pulsed excitation. It can be seen that the dependences are similar in shape: under a constant flow rate, I increases with U and eventually reaches saturation. The highest current amplitudes achieved in the studied two cases were similar and did not exceed

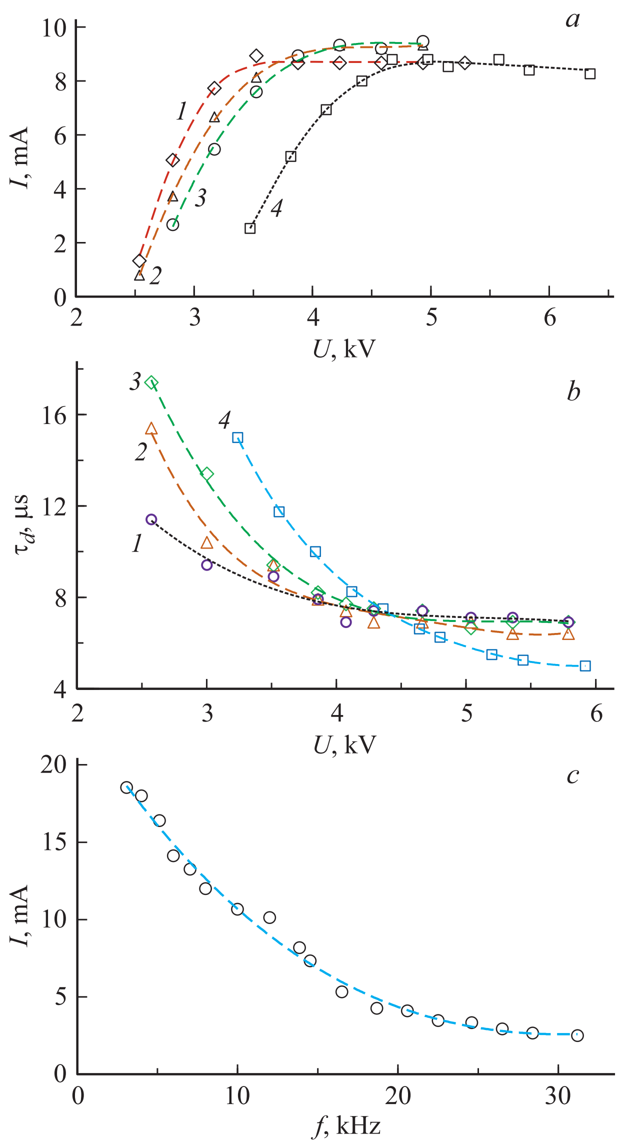

Figure 2. Dependences $I(U)$ (a) and $\tau_d(U)(b)$. $v = 3$ (*1*), 4.5 (*2, 4*), 6 l/min (*3*); $f_0/4 \approx f \approx 13$ kHz; sinusoidal (*1–3*) and pulsed (*4*) excitation. c — $I(f)$, $U = 5$ kV, $v = 4.5$ l/min, pulsed excitation.

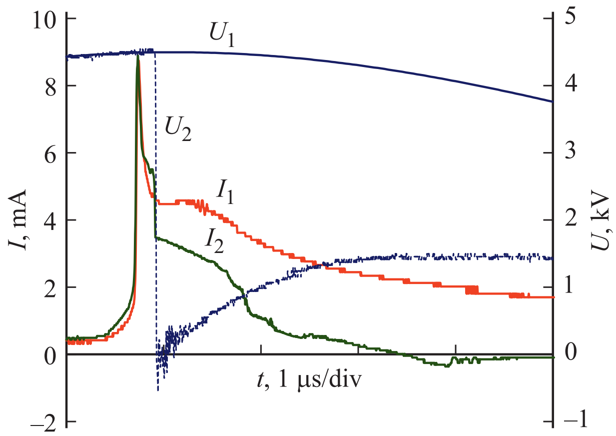

Figure 3. Oscillograms records of voltage at the high-voltage electrode and current at the collector with unlimited (U_1, I_1) and limited (U_2, I_2) duration of current pulses. $f_0 = 21$ kHz, $\upsilon \approx 9$ l/min.

~ 20 mA. At a constant frequency, discharge delay time τ_d (time interval between the start of the positive voltage part and the detection of collector current) decreases as U grows (Fig. 2, *b*).

Investigations of the CPJ parameters at sinusoidal voltage excitation with $f_0 \approx 52$ kHz, as well as in [8] have shown that the frequency of touching the target by current pulses f_I depending on the conditions in the gap nozzle-target is equal or multiple to frequency of applied voltage or is a unit fraction of it: $f_I \approx f_0$, $f_0/2$, $f_0/3$, or $f_0/4$. The minimum frequency was $f_I \approx 13$ kHz. In contrast to the sinusoidal excitation cases [8], f_I under pulsed excitation was found to be equal to f_0. Stable CPJ operation was maintained at all the studied values of parameters U, υ, and z and with all target types. This allowed us to measure frequency response $I(f)$. At $U = 5$ kV and $\upsilon = 4.5$ l/min, the detected current amplitude decreases exponentially as pulse repetition frequency f increases (Fig. 2, *c*). Studies of spectroscopic parameters of a jet above the culture medium surface under different types of excitation and otherwise equal conditions did not reveal any significant differences in compositions and intensities of the generated active components.

Heating of the target surface in the area of its plasma is the limiting factor of CPJ treatment of biological objects at higher CPJ power values. Experiments revealed that temperature T of the dielectric substrate (1-mm-thick Al_2O_3 ceramic material) on a grounded electrode settled within ~ 1 min under CPJ treatment. When a CPJ was excited by sinusoidal voltage with $U = 4$ kV at $\upsilon \approx 9$ l/min, the substrate temperature reached $T \approx 34°$C at $f_0 = 13$ kHz, $T \approx 50°$C at $f_0 \approx 21$ kHz, and $T \approx 87°$C at $f_0 \approx 52$ kHz. It is evident that the maximum achievable substrate temperatures are Studies of spectroscopic parameters for live biological objects. One may limit the current pulse duration to suppress heating. A switch (TGI1-270/12 thyratron with its anode connected to the potential electrode of the CPJ source) was used for this purpose. The switch was actuated in response to a signal from an optical sensor that registered the integrated plasma glow signal upon CPJ current passage. Combined with an adjustable delay, this provided an opportunity to limit the excitation voltage pulse in a controlled mode.

Figure 3 presents superposed oscillograms records of voltage and current under sinusoidal excitation with $U = 4.5$ kV, $f_0 = 21$ kHz, and $\upsilon \approx 9$ l/min obtained with unlimited and limited duration of current pulses. In the latter case, the target temperature decreased by $\sim 20\%$, and the difference grew more significant as U increased. Similar results were obtained under excitation by pulsed voltage.

Thus, it was demonstrated that the achievable parameters of CPJ exposure under sinusoidal and pulsed excitation are identical if the other factors are equal, but the lack of frequency self-organization of streamer breakdown under pulsed excitation makes this regime preferable for biophysical experiments. The target temperature, which may exceed 42°C and become dangerous to living objects, is a limiting factor common to both types of CPJ excitation. This temperature may be reduced by limiting the CPJ current pulse duration.

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Compliance with ethical standards

This article does not contain any studies involving animals performed by any of the authors.

Conflict of interest

The authors declare that they have no conflict of interest.

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