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Investigation of Nonthermal Plasma Jet Excitation Mode and Optical Assessment of Its Electron Concentration

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Abstract: The results of a study of a plasma jet of atmospheric-pressure helium driven by a capacitive discharge using sine and pulsed modes of excitation are presented. The homogeneous discharge of a multi-channel plasma jet at gas temperature of 34 °C and helium flow rate of 0.5 L/min was achieved with short pulse excitation. A digital holography method is proposed to estimate a basic plasma parameter, i.e., its electron concentration. An automated digital holographic interferometry set-up for the observation and study of a nonthermal plasma jet in a pulse mode is developed and described. The synchronization features of recording devices with the generation of plasma pulses are considered. The electron concentration of the plasma jet is also estimated. The disadvantages of the proposed technique and its further application are discussed.

Keywords: plasma jet; bio-medicine application; cold gas-discharge plasma; digital holography; digital holographic interferometry; plasma diagnostics

1. Introduction

Inappropriate and excessive use of antimicrobials and antibiotics creates a problem of acquired resistance of bacteria and parasites to drugs, which is now taking on dangerous proportions. In September 2016, this issue was discussed at the 71st session of the UN General Assembly. Therefore, the development of new physical therapy equipment and non-drug therapies is a very important direction of research in modern science.

Low-temperature plasma has been successfully used in medicine for the last 15 years [1]. The possibility of generating gas-discharge plasma with low gas temperature has led to the development of new and relatively safe methods of non-drug treatment accompanying the surgery of septic wounds [2]; this method is also used in the therapy of more than a dozen skin conditions, as well as in cosmetic procedures that contribute to effective facial rejuvenation, eliminating the need for invasive methods [3,4]. A plasma jet contains charged particles (electrons and ions), generates ozone, nitrogen and oxygen radicals, and produces UV radiation (within the 20–300 nm range), enabling it to destroy the membranes of pathogenic microorganisms. For this reason, treatment with a stream of low-temperature plasma in the therapy of septic wounds can be considered nonspecific, meaning that there is no acquired pathogen resistance [5].

To painlessly treat skin or open wounds, a plasma jet with a low gas temperature (lower than 40 °C) can be used. Such plasma is called non-thermal. The main problem with generating non-thermal plasma jet sources at atmospheric pressure is achieving a low gas temperature of the plasma jet at a low working gas flow rate. In addition, the electrode system of the plasma jets must provide a closed electrical circuit to protect patients from malicious levels of current leakage.

Sine SHF voltage is used to produce a plasma jet with low gas temperature at a low working gas flow rate (<1 L/min) [6]. Typically, SHF power supplies are bulky, expensive and inefficient. Sine HF voltage has the benefit of using power supplies that are more...
compact, but in this case gas temperatures lower than 40 °C can only be achieved at high flow rates of working gas (>3 L/min) [7].

Apart from the gas temperature in the jet and its spatial characteristics, the electron concentration of the plasma is the most important parameter as far as living organisms are concerned. It is obvious that the degree of ionization of working gas can mostly determine the rate of pathogen inactivation or skin regeneration efficiency.

Due to available sensors for the respective frequency ranges, it is easy to measure a radiation intensity in time by means of radiofrequency, optical, or ionizing radiation, i.e., to determine a radiation dose received by the object studied. However, the concept of dose is still not applied in case of treatments by plasma flow; instead, we measure the duration of exposure to plasma along with certain parameters of the electrode system, excitation mode, the type of working gas and the media in which the object is located. To compare the influence of nonthermal plasma jets on living objects, despite the conditions of plasma jet generation, we suppose that the electron concentration of the plasma flow has to be considered. Since plasma has been formed in pulse-periodic mode, probe methods cannot be applied to determine its concentration in the gas flow (gas flow being a non-stationary process). The implementation of spectral methods estimating an electron concentration in gas-discharge plasma [8], however, requires expensive equipment. On the other hand, the holographic interferometry is another method for estimating plasma electron concentration. Within the visible spectral range, it can be used to determine electron or atomic concentrations in the range of $10^{16}$ cm$^{-3}$. However, the use of multispectral holographic interferometry can increase the method's sensitivity by several orders of magnitude [9,10]. Since current holographic interferometry techniques are almost completely digital, it is possible to increase the sensitivity of holographic methods by increasing the dynamic range of digital detectors (CCD- or CMOS cameras) used for hologram acquisition [11].

In this article, we are trying to consider and solve the following problems: the first one is an investigation of the electrode system excitation regimes that can generate a non-thermal plasma jet at a low helium flow rate and low gas temperature; the second one is the development of a reliable method, based on holographic interferometry, to control and estimate the plasma parameters.

2. Materials and Methods

2.1. Testing Electrode System of the Nonthermal Plasma Jet

Tests of several electrode systems (single-barrier discharge with needle electrode, double-barrier discharge and glow discharge) to produce nonthermal plasma flows showed high efficiency and electrical safety of a double-barrier discharge (DBD) electrode system design (Figure 1). High voltage applied to the ring electrodes 2 ignites the gas discharge plasma inside the tube 1, and the gas flow 6 pushes the plasma out in the form of a jet 5.

![Figure 1. Electrode system of plasma-jet-based DBD: 1—glass pipe, 2—ring electrodes, 3—pulsed power supply, 4—gas discharge, 5—plasma jet, 6—gas flow.](image)

Two power supplies were developed to compare the short-pulse and sine excitation regimes of inert gas. The short-pulse power supply was equipped with a MOSFETs-based bridge inverter and a TR1 step-up transformer (Figure 2a). The transistors switched the DC line voltage to the primary winding of TR1 so that high-voltage pulses (2 μs duration)
with long pauses and alternating polarity were generated at the electrodes. Sine voltage power supply is a standard resonant generator (Figure 2b), where the L2-C6-TR2 circuit of elements works as a resonant circuit. Transistors VT5 and VT6 have a duty cycle of 50%, at a frequency close to that of the resonant circuit.

![Figure 2. Electrical circuits of short pulse (a) and sine (b) voltage power supplies.](image)

The high efficiency and long lifetime (up to 8000 h) of XeCl* and KrCl* UV radiators driven by DBD have been well described [12,13]. These results are obtained due to high-frequency short-pulse excitation [14] and a special quartz bulb processing technology [15].

The electrode voltage and gas discharge current were measured with a PPE6KV high-voltage sensor (LeCroy Corp.), a 50 Ohm shunt resistor, and a TEKTRONIX TDS2024C oscilloscope. Helium flow rate did not affect the voltage and current oscillograms. The flow rate was controlled by a PVQ13 proportional valve and PFMV530 flow sensor (SMC Corp.). Plasma gas temperature was measured with a thermocouple thermometer.

At the first stage, we tested the influence of tube diameter, ring electrode length, and interelectrode gap on gas temperature. Optimal parameters of the electrode system in terms of minimum values of plasma jet gas temperature were the same for both short pulse and sine voltages: 5.5 mm tube diameter (glass thickness 0.5 mm), 3 mm width of ring electrodes, and a 5 mm interelectrode gap.

A decrease in helium flow rate led to an increase in gas temperature of the plasma jet (Figure 3). A particularly rapid increase in gas temperature was recorded at the flow rate of less than 1 L/min. However, for excitation with short pulses, this value was much smaller. Thus, for 0.5 L/min, gas temperature was 34 °C for short-pulse excitation and 53 °C for sine excitation. The dependence shown in Figure 3 was obtained at the frequency of 33 kHz and excitation power of 4.2 W for both excitation methods. The excitation power was calculated using the technique described in [16].

Voltage and current of plasma jet at short pulse excitation and at sine voltage excitation shown in Figure 4.

With plasma excitation by microsecond pulses of alternating polarity it was possible to obtain a diffuse plasma jet without contracted channels (Figure 5a). In this case, the gas temperature of the plasma jet was 34 °C at a helium flow rate of 0.5 L/min.

Obviously, the larger the contact area of plasma with the treated surface, the less time it will take to treat it. In order to increase the diameter of the plasma flow, a multi-channel electrode system was tested. To implement this system, electrode systems absolutely identical to the construction demonstrated in Figure 1 were installed parallel to each other in one housing case (Figure 5b). The electrodes were supplied from a single power source. By means of a splitter, the helium flow was supplied to the channels at the same flow rate. The tests showed that all channels of the plasma jets could operate in parallel without affecting each other. The application of the three-channel plasma jet allowed us to increase the area of plasma contact with the surface up to 1 cm². To obtain an even larger diameter of the plasma jet, it was necessary to increase the number of plasma jet channels.
Figure 3. Dependence of plasma jet gas temperature on flow rate at short pulse (○) and sine (△) excitation voltage.

Figure 4. Voltage and current of plasma jet at short pulse excitation (a) and at sine voltage excitation (b).

Figure 5. (a)—Helium plasma jet at short pulse excitation, (b)—three-channel plasma jet.
2.2. Evaluating of Electron Concentration in Non-thermal Plasma Jet Generated at Pulse Excitation

As we have already mentioned, the problem of plasma diagnostics can be solved by different methods. However, it would be prudent to have a sufficiently reliable and flexible method for estimating the concentration of plasma particles, and digital holographic interferometry is a proper method for this task. The results of the application of this method are preliminary and demonstrate the principal possibility of digital holographic interferometry for the investigation of a non-thermal plasma jet generated at pulse excitation.

The investigation of plasma by holographic methods is based on the study of a phase (transparent) object, in which the phase changes of the object field depend on the spatial localization of the object and its refractive index [17]. The obtained values of the plasma refractive index allow us to calculate its electron concentration [18].

It is well known in holographic interferometry that phase difference is related to the corresponding refractive index by the following expression

$$\Delta \varphi(x, y) = \frac{2\pi}{\lambda} \int_{l_1}^{l_2} [n(x, y, z) - n_0]dz$$ (1)

where $n(x, y, z)$ is the refractive index of the medium (plasma), and $n_0$ is a refractive index of the medium against which the comparison is being made [19]. The integration limits determine the length of the path along which the probing radiation propagates.

In conventional (analog) holographic interferometry, fringe analysis is carried out with the accuracy of phase detection associated with changes in the optical path up to $\lambda/10$ [20]. However, in digital holographic interferometry, holograms are recorded digitally, where the phase detection accuracy is determined by the dynamic range of the detector, with the 8-, 10- or 16-bit resolutions of an analog-to-digital converter. Thus, with 8-bit, it is possible to increase the phase detection sensitivity up to $\lambda/256$ [11].

Digital holographic interferometry is based on a comparison of the phases of at least two optical wavefronts recorded at different moments in time as digital holograms. The result of the phase comparison between the wavefronts is represented as a numerical phase difference map [21].

A digitally recorded hologram is the distribution of the interference patterns from a superposition of reference and object beams on the detector. The correct acquisition of the hologram can be provided if the condition for the sampling theorem has been met [22]. This theorem determines the angle between the reference and object beam

$$\alpha_{\text{max}} = \frac{\lambda}{2\Delta x}$$

where $\Delta x$—is the pixel size of the detector. The evaluation of the holograms and phase reconstruction were performed using the Fourier transform method [23]. If holograms are recorded at time moments $t_1$ and $t_2$, corresponding to different object states, it is possible to calculate the phase difference after the reconstruction routine.

Result intensity recorded on the camera sensor is:

$$I(x, y) = |E_R \exp(-i\varphi_R(x, y)) + E_o \exp(-i\varphi_o(x, y))|^2 \times |E_R \exp(-i\varphi_R(x, y))E_o \exp(-i\varphi_o(x, y))|^2$$ (2)

where $E_R$ and $E_O$—are the amplitudes of the reference and object waves, respectively.

Applying double Fourier transform, followed by filtering and inverse double Fourier transform for different states of the object, allows one to obtain the phase difference function:

$$\Delta \varphi = \arctg[tg(\varphi_1 - \varphi_2)] = \arctg\left[\frac{Im_1 \times Re_2 - Im_2 \times Re_1}{Im_1 \times Im_2 + Re_1 \times Re_2}\right]$$ (3)

which describes the change in the state of the object [24].
Thus, for example, if an object is subjected to mechanical loading, the phase difference will be related to the value and direction of displacements of the object’s surface points [25]. When a phase object is investigated, phase difference will be determined by the integral change of the optical path related both to the size of the object and to spatial distribution of the refractive index of the medium according to the equation (1). In a simple way, the relation between the plasma refractive index and its electron concentration is determined by the following relations:

\[
n - 1 = \sum_{i=1}^{k} \left( A_i + \frac{B_i}{\lambda^2} \right) N_{a_i} - 4,5 \times 10^{-14} \lambda^2 N_e \tag{4}
\]

where, \( A_i \) and \( B_i \) are the Cauchy’s constants for the medium, \( \lambda \)—is the laser radiation wavelength, \( N_e \)—is the plasma electron concentration, \( N_{a_i} \)—are atomic concentrations [26], and the phase difference is, respectively:

\[
\Delta \varphi(x, y) = \frac{2\pi}{\lambda} l \Delta n
\tag{5}
\]

where \( \Delta n \)—is the change in the refractive index, and \( l \)—is the optical path length along the medium under study.

2.3. Experimental Setup (Experimental Verification of Pulsed Plasma Jet Registration)

The optical setup for an investigation of a non-thermal plasma jet allowed for the acquisition of the image plane hologram of the area where the phase object was localized. The setup is represented in Figure 6 and its laboratory configuration in Figure 7.

Output laser radiation was collimated to a diameter of about 15 mm and then split into the reference and object beams. Since the coherence length of the laser was 5 cm, the optical paths of the reference and object beams were aligned to an accuracy of 5 mm. The object beam, passing through a jet of nonthermal plasma, experienced a phase difference. Comparing the holographic images recorded at the moment of plasma generation and the moment of its absence made it possible to evaluate the phase changes corresponding to the refractive index of plasma.

**Figure 6.** Configuration of the digital holographic interferometry complex for the study of plasma flow in the pulsed generation mode: (1)—Nd: YAG pulse laser, (2)—CCD Camera, (3)—pulse-plasma generator, (4)—helium container, (5)—collimator, (6, 7)—beam splitters, (8, 9, 10, 11)—mirrors, (12, 13)—lenses, (14)—plasma jet, (15)—synchronization Unit, (16)—PC.
The nonthermal plasma jet was generated in pulsed mode with a frequency of 5 kHz and a pulse duration of 750 ns.

In the pulse mode of plasma generation, it is only possible to record holograms when the laser, the digital camera, and the plasma generator are synchronized with each other. Thus, we used an InnoLas “SpitLight Hybrid II” pulsed laser, with a maximum pulse repetition frequency of 50 Hz and a duration of 10 ns, and a Pulnix 1325 CL CCD camera, with a minimum exposure time of 62 µs and a frame repetition rate of 15 fps, in order to acquire holograms. A short laser pulse duration avoids the influence of random changes in the medium, which can destroy the phase information due to its averaging. Synchronization of all devices was carried out by using the NI-DAQ (National Instruments data acquisition) boards NI USB 6258 and NI SCB 68, as well as developing a hardware-software algorithm in the LabVIEW environment.

Since the frame rate of the camera and laser pulse frequency are significantly lower than the repetition rate of plasma, the recording of holograms corresponding to the plasma single-pulse is only possible when a number of plasma pulses are skipped between the hologram acquisition. Hence, the synchronization of the devices was realized in the following conditions: 15 Hz for the laser and camera repetition rates, and 4995 Hz for the plasma pulse generator. Such configuration corresponds to skipping 333 periods of plasma pulses between each moment of laser pulse “shots” and the image recording. All devices were triggered simultaneously from one external synchronizing source at the beginning of the measurement. However, due to the large difference in the frequencies of plasma pulses and the laser-camera system, the plasma pulse and trigger signal of the laser-camera had a mismatch of 60 ns in one cycle. Therefore, the trigger signal for the laser-camera shifted 60 ns along the plasma pulse. This mismatch allowed for the “scanning” of the plasma pulse that had a 750 ns duration, under the assumption that the occurring processes were identical and stationary.

3. Results

The proposed setup recorded a set of holographic images in the following sequence: holograms in the absence of helium in the observation chamber (with only air inside),...

Figure 7. Configuration of the digital holographic interferometry setup for the study of plasma flow in the pulsed generation mode (photograph).
holographic images when helium was supplied, images under plasma generation, and finally, the images with helium but when the plasma was turned off.

Therefore, it was possible to compare the following phase changes for refractive indices, for $\phi_a$—phase in air, $\phi_h$—phase in helium, and $\phi_{hp}$—phase in helium in the presence of a plasma pulse, namely, the observation of the phase difference $\Delta \phi_{ha} = \phi_h - \phi_a$ (helium—air), $\Delta \phi_{hp} = \phi_{hp} - \phi_a$ (helium + plasma—air), and $\Delta \phi_p = \phi_{hp} - \phi_h$ (helium + plasma—helium), provided that the image acquisition system was properly synchronized.

Figure 8 shows interferograms of gas flow development in air, where the white frame highlights areas in which phase changes were identified. Figure 8a depicts the phase difference with the initial state of helium flow before the appearance of plasma ($\Delta \phi_{ha}$). The highlighted region in Figure 8b shows changes associated with the onset of plasma formation ($\Delta \phi_{hp}$). Further on until plasma generation was completed, the distribution of fringes corresponding to that process is shown in Figure 8c. After the completion of plasma generation, phase difference distribution returned to the initial state as shown in Figure 8d.

It is important to note that the changes in interference patterns associated with the appearance of plasma correspond to the duration of the plasma jet ($t_{plasma} = 750$ ns).

In order to show the influence of the plasma on the refractive index, the phase difference $\Delta \phi_p$ was evaluated. Figure 9a shows the phase difference for the helium flow only. The phase distribution is uniform, and no other processes appear. Figure 9b shows the phase difference between the moments of gas with plasma and in its absence. This interferogram demonstrates the phase change that is distributed along the direction of plasma jet formation. Figure 9c shows an interferogram of the phase difference at 700 ns after the end of plasma generation. The figure shows an asymmetric intensity distribution, which may be associated with the residual transient processes in the gas after the plasma generation.
decay. Based on the phase distribution and without taking into account neutral atoms, we estimated the peak electron concentration at $0.9 \times 10^{16}$ cm$^{-3}$.

4. Discussion

As shown in Figure 4, gas discharge current in pulsed excitation is much shorter than in sine excitation. Short pulses of current flowing through plasma eliminate the overexcitation of gas discharge, while long pauses provide the relaxation of gas-discharge plasma. This method of excitation by short pulses makes it possible to obtain a diffuse plasma jet without contrasting channels and local plasma overheating (Figure 5). On the other hand, long excitation pulses lead to plasma contraction, plasma resistance decrease, and an increase in gas temperature.

Unlike conventional interference methods of plasma observation, the digital holographic interferometry technique makes it possible to digitally evaluate the phase difference over the entire observation field, as well as to fully automate data acquisition and processing [10].

The results do not allow us to definitely conclude that the recorded phase changes are completely related to plasma refraction, and that the neutral atoms, according to expression (4), have no effect on the phase shift. Thus, we have not yet been able to perform an accurate analysis of the electron concentration in the plasma. This method requires further improvements to increase its sensitivity, accuracy and reliability of synchronization. The sensitivity can be improved by switching to another spectral range, which will allow us to take into account the influence of neutral atoms on the resulting interferogram [25]. Increasing the accuracy of synchronization can provide precise locking of the image acquisition related to the beginning of plasma–pulse duration. It is also possible to use ultrahigh-speed digital cameras.

Figure 9. Phase difference: (a)—phase difference corresponding to the initial state; (b)—phase difference with plasma; (c)—phase difference at 700 ns after the end of plasma jet.
5. Conclusions

In this work, we show that the gas temperature of nonthermal plasma flow depends not only on the configuration of the electrode system, the excitation power level, and the rate of inert gas pumping, but also on the form of the voltage applied to the electrodes. Applying pulses of microsecond duration with long pauses leads to low values of the plasma flow temperature at a minimum level of helium flow rate.

We have also been able to demonstrate in principal the possibility of using digital holographic interferometry to register and observe refraction in pulsed plasma. We were able to see a change in the refractive index both with and without gas jet ionization. Further improvement of the technique will allow us to estimate the concentration of electrons in order to determine the dosage of plasma used in skin treatment.

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