Physical features of atmospheric pressure microdischarge system with vortex gas flows

Abstract: The parameters for microdischarges of plasma medicine in air and argon vortex flows at atmospheric pressure for different shapes of electrodes (outlet nozzle and axis electrode diameters ratio set) have been investigated. The current-voltage characteristics of the designed systems have been analyzed, the parameters of the generated jets plasma have been investigated by means of the optical emission spectroscopy, and the form of plasma jets has been studied by using video camera.

Keywords: microdischarge, gliding microdischarge, microjet, glow discharge, emission spectroscopy.

DOI: 10.1515/chem-2015-0043
received February 07, 2014; accepted May 30, 2014.

1 Introduction

Microdischarge plasma generation is considered to be one of the most promising areas of non-equilibrium plasma chemistry today and can be applied in different fields: for the environmental protection, in biology and biomedicine, as an ultraviolet and vacuum ultraviolet intense source, and for the surface activation and films deposition. Currently there is no full understanding of the microdischarge physics nature, and therefore it is impossible to do the detailed analysis of their parameters. Microdischarge plasma is characterized by significant changes of the excited states distribution function and ions and electrons energy in a relatively short time. It is possible to use such discharges as the sources of reactions active components.

The medical area is interested in the different microplasma systems to ensure by their ability to generate low-temperature non-equilibrium atmospheric pressure plasma (NAPP). The electron temperature in NAPP is a few eV, which is usually sufficient, to initiate a group of chemical reactions including – proteins, cell membranes and DNA modification; and producing radicals. At the same time, the heavy particle temperature is close to room temperature; therefore the plasma treatment does not destroy temperature sensitive biological tissues. The disinfection, decontamination and sterilization processes that uses active plasma particles (radicals, charged particles, excited particles, UV radiation) occurs quite rapidly under such conditions. Experiments have shown several seconds to several minutes of the plasma treatment is necessary for different types of viruses and bacteria neutralization on surfaces and in aqueous solutions. The following applications of plasma systems in medicine are known from the literature [1-3]: sterilization, cancer cells destruction, blood coagulators (to stop bleeding), and wound healing, whitening and cleaning teeth. It was shown that plasma usage in combination with well-known traditional medical methods significantly increases its efficiency.

Currently, there are two main applications of NAPP for disinfection, decontamination and sterilization. For the first application, the plasma generation is remote, and the products of its afterglow are delivered to the biological tissue in a loop. The therapeutic effect is probably provided by the neutral particles and radicals with long-term existence, while the majority of charged particles disappear outside the plasma generation zone. Usually, in order to avoid plasma instability, the work should be carried out with helium or argon diluted gases, and the discharge is doped with just a few percent of molecular...
gases, for example – oxygen. Plasma jets generators are used for realization of this approach [4-6]. Previous studies have demonstrated that using a remote plasma sources provides the more focused surface sterilization than by using a large plasma volume.

The second approach suggests that plasma is generated while in direct contact with living tissue. When using the dielectric barrier discharge, the plasma device has one power supply electrode and the counter electrode is biological tissue [1]. This approach differs from the previous application in two keys ways. First, the plasma spreads and touches the biological surface which enables its charging and high-energy ions delivery and second, the magnitude of the electric field created on the surface, is several orders greater than in the case of indirect plasma contact.

The first or the second approach can be used depending on the specific case.

A lot of devices for microplasma jet generation have been based on different discharges: dielectric barrier, glow [7], etc. Most of them operate at tens kV [1]. The safety of plasma systems decrease when they o with living biological objects and that is why the microdischarge is perspective promising low-voltage plasma jets generators for biomedical applications as it operates at significantly lower supply voltage (U \sim 300 V).

A microdischarge system with a vortex gas flow was designed and studied in this work. Previous work has shown that a dynamic gas-discharge system could be efficiently used for water disinfection [8]. Previous studies have determined that the parameters of the plasma jet in the system, based on the discharge in the Tornado type reverse vortex gas flow with liquid electrode revealed inability of that plasma usage with living tissue treatment due to high gas temperature (molecules rotational temperature: T^{\ast}_{r}(\text{OH}) \sim 3200\pm200 K [8], T^{\ast}_{r}(\text{N}_2) \sim 3100\pm500 K [9]). The significant reduction of electrode system geometrical sizes is, in all likelihood, required in order to maintain the heavy particles temperature at the level of the environmental temperature.

2 Experimental procedure

An axially symmetric microdischarge system with a vortex gas flow has been used for atmospheric pressure plasma jet generation (shown on Fig. 1b). The electric scheme of this generator is shown on Fig. 1a. It is possible to change the electrodes polarity in this microdischarge system. The external electrode (1) has a flat part of 1 mm in width and 20 mm in diameter with an outlet in the center.

The second cylindrical electrode (2) of 1 mm in diameter is placed on the axis of the system. Electrodes are separated by a Teflon dielectric (3). The working gas (air or argon) is induced tangentially into the lateral surface of the electrode (1) through the outlet (4) of 1 mm in diameter in order to assure the swirling of gas flow in the interelectrode gap. It is possible to change distance between electrodes (l) in this microdischarge system.

3 Results and discussion

The current-voltage characteristics (CVC) of the microdischarge with vortex flow for different working
gases (air, argon) and their flows $G$ (0.5, 1, 2 and 4 L min$^{-1}$), polarities of electrodes, interelectrode gaps $l$ (0.4 ÷ 3 mm) and diameters of the outlet – $d$ (0.5 and 1.7 mm), have been investigated in this research. The form and the length of plasma jet have been analyzed during the experiment by using video camera (Fig. 6). It should be noted that the choice of the outlet diameter has been based on the internal electrode diameter ratio. Thus, the “Tornado”-type discharge was obtained by implementation of a system with $d = 0.5$ mm, and $d = 1.7$ mm. The discharge for the rotating sliding arc mode generation has been closed.

The CVCs of the microdischarge with vortex gas flow for different interelectrode gaps are shown in Fig. 2.

Fig. 2 shows the interelectrode distance increase at the burning voltage level amplification. All of the studied air flows show a regularity for the both electrode plate polarities. Also, the non-monotonous CVC current is best revealed with the electrode plate with a negative polarity in the studied area. This regularity is seen for $d = 0.5$ mm (Fig. 2b), and $d = 1.7$ mm (Fig. 3b), with air flow $G = 2$ and 4 L min$^{-1}$ (Fig. 4b).

The influence of the working gas composition on the microdischarge voltage has been established. The current-voltage characteristics in relation to the discharge current for different gases are shown on Fig. 5. The presented figures demonstrate that the transition from the molecular gas to the inert one is accompanied by a significant decrease in the burning voltage level (almost by 50% at the minimum test current). Additionally, the discharge area with a positive differential resistance is observed at the CVC when dealing with an inert gas. It allows a parallel connection of several discharges to the single power source.

Fig. 5 shows that the microdischarge burning voltage when using argon is almost 2.5 times lower than the corresponding values for air at a fixed discharge current (in the range of $I \leq 40$ mA, Fig. 5b). This means that argon makes it possible to operate the microdischarge at a lower power ($P \leq 10$ W) for both polarities of the flat electrode, for all investigated diameters of the gas outlet and flows, $G$. As a result of this the electrodes heating decreases by almost 50% when using argon.

A comparative analysis of the energetic parameters of microdischarge with different diameters of the gas outlet $d$ (0.5 and 1.7 mm) does not reveal a significant difference in the CVC behavior. At the same time, diameter of the
gas outlet (the ratio of the gas outlet and axial electrode diameters) noticeably influences on the discharge burning mode and on the plasma jet form. Photos of microdischarge plasma jet are presented on Fig. 6 for different air flows, G, and gas outlet diameters.

The maximal length of the plasma jet, $Z = 18$ mm (Fig. 6a), is observed for a smaller diameter of the gas outlet ($d = 0.5$ mm) and air flow, $G = 0.5$ L min$^{-1}$. When the air flow is increased up to $3$ L min$^{-1}$, the length of the jet decreased, and the tip is widened (Fig. 6b). A change of the jet form and length has been observed for the positive polarity of the flat electrode. Thus it can be concluded that the plasma jet form and length depends on the gas flow, G, for the both polarities of the flat electrode.

As described above, the choice of outlet diameter and axial electrode ratio affects the jet form and length. Thus, when the outlet diameter equals 0.5 mm, the special mode “Tornado” type for discharge formation is implemented (narrow plasma microjet Figs. 6a, 6b). When the outlet diameter equals 1.7 mm, the special mode, close to rotating sliding discharge formation is implemented [9] (Fig. 6c). It has been demonstrated that jet becomes narrower and longer (almost twice) when the gas outlet $d=0.5$ mm (Fig. 6a) than $d = 1.7$ mm (Fig. 6c) at the same polarity of electrodes and inter-electrode gap.

It was shown that a plasma jet is not blown out from the outlet of 0.5 mm in diameter when using argon.
A mode, which is similar to the rotation gliding discharge with maximal length of 2 mm, has been realized for gas outlet of 1.7 mm in diameter.

Optical emission spectroscopy of the microdischarge plasma has been carried out perpendicular to the plasma jet. Spectra have been registered using Solar TII spectrometer S-150-2-3648 based on the CCD lines in spectral area of 200-1100 nm with spectral resolution ~ 0.2 nm. An emission spectra of Ar microplasma in the open air has shown bands of Ar I (763.5, 811.5, 842.5, 852.0, 912.0 nm, etc.) lines, O I (777.2, 844.6 nm) lines and OH (A-X) at 309.6 nm and N₂(C-B) at 337.6 nm.

The electronic excitation temperature, Tₑ*, of O and Ar atoms in generated microplasma has been determined by Boltzmann plots by using relative intensities of O I (777.2 and 844.6 nm) and Ar I (763.5, 811.5, 842.5, 852.0, 912.0 nm) lines and has been calculated at Tₑ*(O) ≈ Tₑ*(Ar) ≈ 2000 K.

4 Conclusions

- It is shown that the microdischarge with a vortex gas flow operates in the power range of P = 1 ÷ 30 W. The current-voltage characteristics analysis of the investigated microdischarge shows that all types of glow discharge (subnormal, normal and abnormal) can be realized within the investigated discharge current range. It has been shown that part of this range, which corresponds to the normal glow discharge, is quite small.
- There is a possibility of implementing two different modes of microdischarge burning according to outlet and axial electrodes diameters ratio: the “Tornado” type reverse vortex flow with the generation of narrow plasma microjet and gliding rotating microdischarge with rotating plasma jet.
- The main feature of this microdischarge is its ability to operate at low voltages (in the case of argon flow: U ≈ 200 V at P = 1 W).
- A slight current-voltage characteristics growth with interelectrode gap increase has been observed. A non-monotonic character of the voltage dependence on the inter-electrode gap has been demonstrated for negative polarity of the flat electrode. It was found that graphical forms of this dependence vary for different gas flows.
- The electronic excitation temperature, Tₑ*, of O and Ar atoms in generated microplasma has been determined by Boltzmann plots and has been calculated at Tₑ*(O) = Tₑ*(Ar) = 2000 K.

References

[1] Park G.Y., Park S.J., Choi M.Y., Koo I.G., et.al., Plasma Sources Sci. T, 2012, 21, 21
[2] Weltmann K.D., Kindel E., Woedtke T., et al., Pure Appl. Chem., 2010, 82(6), 1223
[3] Fridman A.A., Plasma Chemistry, Cambridge University Press, Cambridge, 2008, 978
[4] Laroussi M., Akan T., Plasma Process. Polym., 2007, 4, 777
[5] Laroussi M., Lu X., Appl. Phys. Lett., 2005, 87, 3
[6] Algwardi Q.Th., D. Appl. Phys. Lett., 2011, 99, 3
[7] Fridman A., Friedman G., Plasma Medicine, 2nd edition, John Wiley & Sons, 2013, 545
[8] Nedybaliuk O.A., Chernyak V.Ya, Olzewski S.V., Martysh E.V., Int. J. Plasma Env. Sci. & Technol., 2011, 5(1), 20
[9] Nedybaliuk O.A., Olzewski S.V., Chernyak V.Ya., Lomonos O.I., Solomenko Ok.V., Shykht I.G., Bulletin of Taras Shevchenko National University of Kyiv: Series physics & mathematics, 2010, 1, 180, http:/bulletin.univ.kiev.ua/ukr/bulletin.html