Direct and Indirect Studies of the Gaseous Charged Species in Surface Dielectric Barrier Discharge in Plasma Actuator

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***Abstract*—In this paper we present results of the studies on the gaseous charged species produced in the surface dielectric barrier discharge (SDBD). In this study two experimental method were used: direct - optical emission spectroscopy of the SDBD plasma and indirect - trajectory tracking of the microparticles (previously charged by the SDBD ionic wind) travelling in the external electric field. In these experiments a SDBD actuator with an air-exposed high voltage electrode and an air-insulated grounded electrode was used to generate the surface SDBD. The spectroscopic measurements showed that the SDBD spectrum is dominated by the second positive system of N_2 molecules. The spectral band of the first positive of N_2^+, NO and OH, as well as the atomic lines of O were also identified in the SDBD spectrum. The N_2^+ ion was identified as main positive charge carrier in the ionic wind generated by the SDBD. The results of the trajectory tracking of the microparticles revealed that in the external electric field particles undergo the effect of separation of direction of movement (they travel according or contrary to the electric field lines).**

Keywords—DBD; surface dielectric discharge, electric discharge; optical emission spectroscopy; particle tracking

I. Introduction

In recent years applications of the surface dielectric barrier discharge (SDBD) in industrial applications expand. The new areas of the SDBD applications are: active aerodynamic flow control in the SDBD actuators [1], [2], surface treatment [3], [4] and air and water purification [5], [6].

A large number of research groups in the world have been working for years on the SDBD with objective of improving its performance for plasma actuators [1]. Although there are essential improvements in understanding the physical aspects of the SDBD and the electromechanical conversion, there is still a stagnation in the practical improvement of SDBD actuators in terms of the generation of actuator force/force effectiveness and electric wind velocity. It is a common opinion that controlling the generation of electric charges in the SDBD is a key point for improving the performance of SDBD actuators.

In this paper we present results of the experiments on the identification of electric charges generated in the SDBD typical of the flow actuators. For that purpose we employed a direct method of the optical emission spectroscopy (OES), which usually is a powerful tool for identifying neutral and charged gaseous species in the electrical discharges. However, it has appeared that the radiation spectrum emitted by the SDBD had not provided sufficient information for defining the main electric species generated in the SDBD. To get more information on the gaseous charged species produced in the SDBD we used an indirect method based on introducing the microparticles into the SDBD and studying their electric charge, which they acquired from the gaseous charged species produced in the SDBD.

II. Experimental

A. Basic setup for SDBD generation

In this experiments two variants of the experimental setup were used. The first for the optical emission spectroscopy of the SDBD plasma and the other for the microparticle tracking. In both cases the basic apparatus for the generation of the SDBD discharge was alike. Namely, it consisted of a classic SDBD actuator [7], a sine-wave signal generator coupled with a high voltage amplifier and a digital oscilloscope with a high voltage probe (the apparatus in the configuration for spectroscopy measurements is shown in Fig. 1). The SDBD actuator had an air-exposed high voltage electrode and an air-insulated grounded electrode imbedded. The electrodes for the actuator were made of 50 μm-thick copper foil and were placed on the opposite side of the 2 mm-thick glass plate, which acted as the dielectric barrier (relative electric permittivity $\varepsilon_r = 7$). The sinusoidal signal with a frequency of f = 1kHz, generated by Tektronix AFG3252, was amplified by Trek 40/15 to have a peak voltage of U_{pp} = 20 kV and applied to the high voltage electrode. The other electrode, insulated from air with a kapton polymer type was grounded. The high voltage signal was monitored by the Keysight DSO 9064A oscilloscope with the Tektronix P6015A probe. The experiments were carried out in ambient air at atmospheric pressure.

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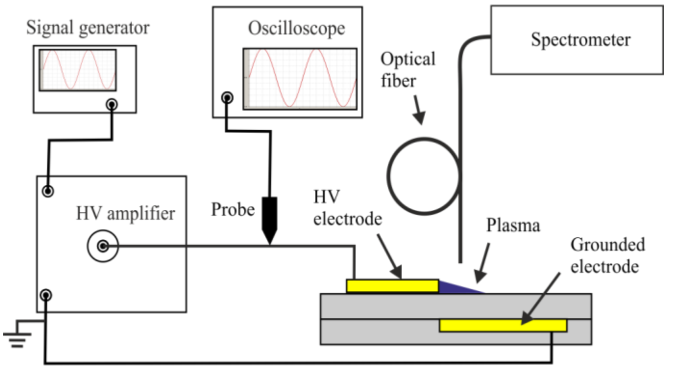

Fig. 1. Experimental setup for the optical emission spectroscopy of the SDBD.

B. Setup for optical emission spectroscopy

The emission spectra of the SDBD plasma radiation was registered with an Echelle-type, optical-fiber spectrometer Andor Mechelle 500 integrated with an iStar ICCD (intensified CCD) camera. The spectral range of the spectrometer was from 240 nm to 885 nm. A bare input end of the optical fiber (without a ferrule) was placed 5 mm above the plasma actuator and 1 mm from the electrode edge as shown in the Fig. 1. A numerical aperture of the optical fiber was 0.22, thus spectrometer registered the radiation emitted from the area of a base of 2.3 mm in diameter into a cone.

C. Setup for microparticle tracking

The measurement procedure for 2D particle tracking is based on recording a set of images of the measurement region in the so-called laser sheet formed from a pulsed laser beam, and next locating the microparticle of interest in every recorded image using a computer algorithm. The detailed description of the microparticle tracking procedure can be found in [8].

The experimental setup for the microparticle tracking was composed of a pulsed Nd:YLF laser system (Litron LDY304, $\tau = 150$ ns, $E_i = 30$ mJ, $f = 200$ Hz, $\lambda = 527$ nm) with a laser sheet forming optics, a high speed CMOS camera (Speedsense M340) and a computer with analytic software Dantec Dynamic Studio (Fig. 2). The traced microparticles (average 10 µm in diameter) were made of milled aluminum oxide (Al_2O_3).

Before the experiment a pinch of Al_2O_3 was settled on the upper surface of the SDBD actuator (the glass plate) 3 mm from the edge of the high voltage electrode. The electrohydrodynamic (EHD) air flow, generated by the SDBD actuator, carried the Al_2O_3 microparticles into the volume between two parallel plate electrodes located 5 cm away from the actuator. The plate electrodes (made of a 1 mm think copper sheets), having dimensions of 130 mm x 200 mm were placed 60 mm apart from each other. The static electric field between the electrodes was formed by a + 5 kV positive voltage, applied to the upper electrode. The lower electrode was grounded.

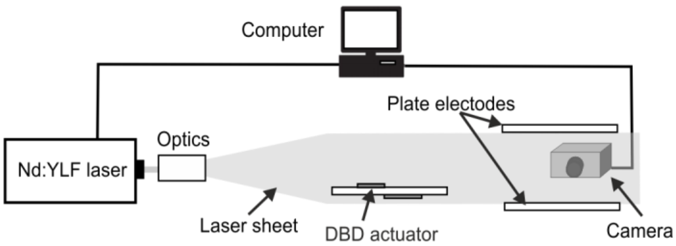

Fig. 2. Experimental setup for the microparticle tracking. The power supply part of the experimental setup was not shown in the scheme. The DC voltage of +5 kV was applied to the top plate electrode, the bottom electrode was grounded.

The EHD air flow contained the gaseous charged species produced by the SDBD. When encountering the Al_2O_3 microparticles the gaseous charged species charged the microparticles according to the electric polarity they had (positive or negative). Therefore, majority of the Al_2O_3 microparticles entering the volume between the two parallel electrodes are charged, positively or negatively, depending on the polarity of the gaseous charged they collided with.

The microparticle tracking system, focused onto the volume between the two parallel plates monitored the trajectory of the Al_2O_3 microparticles in the external electric field. The recorded trajectories enable judging the charge of the Al_2O_3 microparticles, and indirectly the charge of the gaseous charged particles produced in the SDBD.

III. Results

A. Plasma emission spectroscopy

The emission spectra of the SDBD plasma captured at the rising and falling edges of the sine-wave voltage cycle are given in the Fig. 3. Due to a relatively low intensity of the radiation emitted by the plasma in one voltage half-cycle the spectra shown in the Fig. 3 were averaged over 10 000 half-cycles.

The spectral bands and lines shown in the Fig. 3 were identified using the NIST database [9]. Since most of them are located in the near UV and visible range the spectral range in the graphs was adequately cropped.

When the SDBD is generated in air an energetic free electrons collide with the air molecules resulting in dissociation, ionization and excitation of the air molecules [10]. Thus the SDBD emission spectra is expected to consist mainly of the second positive band of N_2 molecules. The N_2 bands were found for both spectra captured at the rising and falling edges of the applied voltage cycle. The weaker bands of the first negative of N_2^+, NO and OH (from the dissociation of the water vapour contained in air), as well as the atomic lines of O were also observed in the plasma spectra. However the O lines were observed only for the rising voltage edge. The description of the reactions responsible for the formation and excitation of radicals (O, NO, OH) from the air molecules in the DBD plasma can be found in [2].

The spectroscopic results of this study suggest that the dominant positive charge generated in the SDBD is N_2^+, which may be identified as the main ion responsible for the positive charge carrier. This is inconsistent with the analytical model the DBD proposed by Linsheng et al. [12], who identified O_2^+ as the main positive ion generated in the discharge due to its lower ionization energy than N_2^+ [13]. On the other hand, model proposed by Pinheiro et al. [14] supports the thesis about the N_2^+ ions as dominant positive specie generated by the DBD in the air.

Most of the negative ions generated in the DBD discharge are produced via the process of electron attachment to the electronegative O_2 molecules [12]. Apart from the electrons the negative O_2^- ions are believed to be the dominant negative charges carriers generated in the discharge. However we were not able to find any radiation of the O_2 molecules and ions in the SDBD plasma spectrum.

The emission spectroscopy method has not provided sufficient information about the gaseous charged species produced in the SDBD. Though the existence of the negative charge carriers can be indirectly confirmed by analyzing the behavior of the microparticles charged by the ionic wind of the SDBD plasma. This is due to the fact that the main mechanism of microparticles charging is by charge transfer during a collisions of particles with the ions contained in EHD air flow [15].

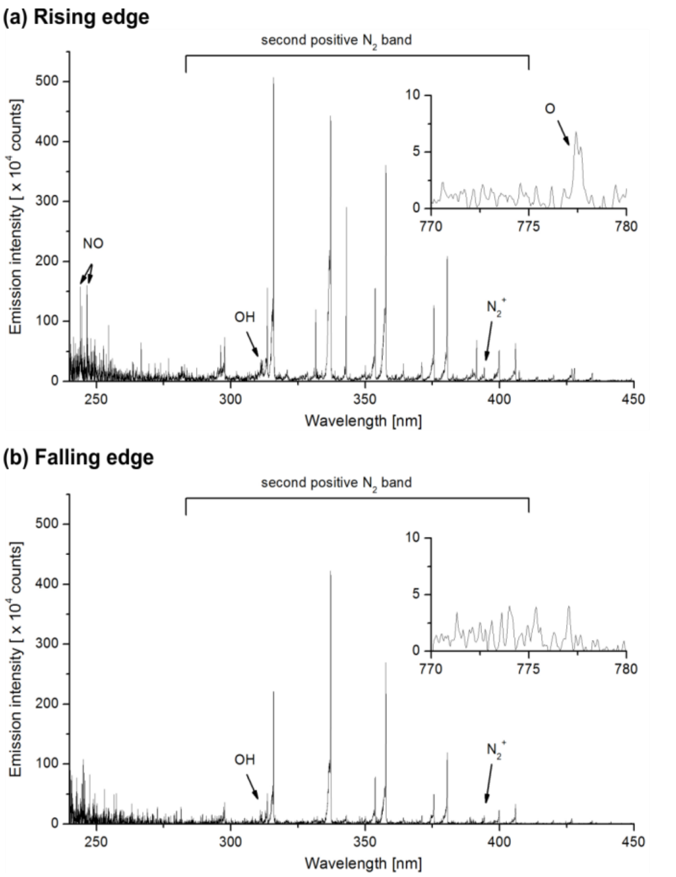

Fig. 3. The emission spectra of the DBD for the (a) rising and (b) falling edge of the voltage cycle.

B. *Microparticle tracking*

In this part of the experiment the microparticles charged by the SDBD enter the measurement region between two plate electrodes. Initially the voltage was not applied to the plate electrodes. The time of applying the voltage to electrodes was taken as the reference time t = 0 (the voltage rising time was 5 ms).

The trajectories of movement of the microparticles obtained using the particle tracking method are presented in the maps in the Fig. 4. Each map shows the particle trajectories in the different time interval from t = -1 s to t = 6.5 s.

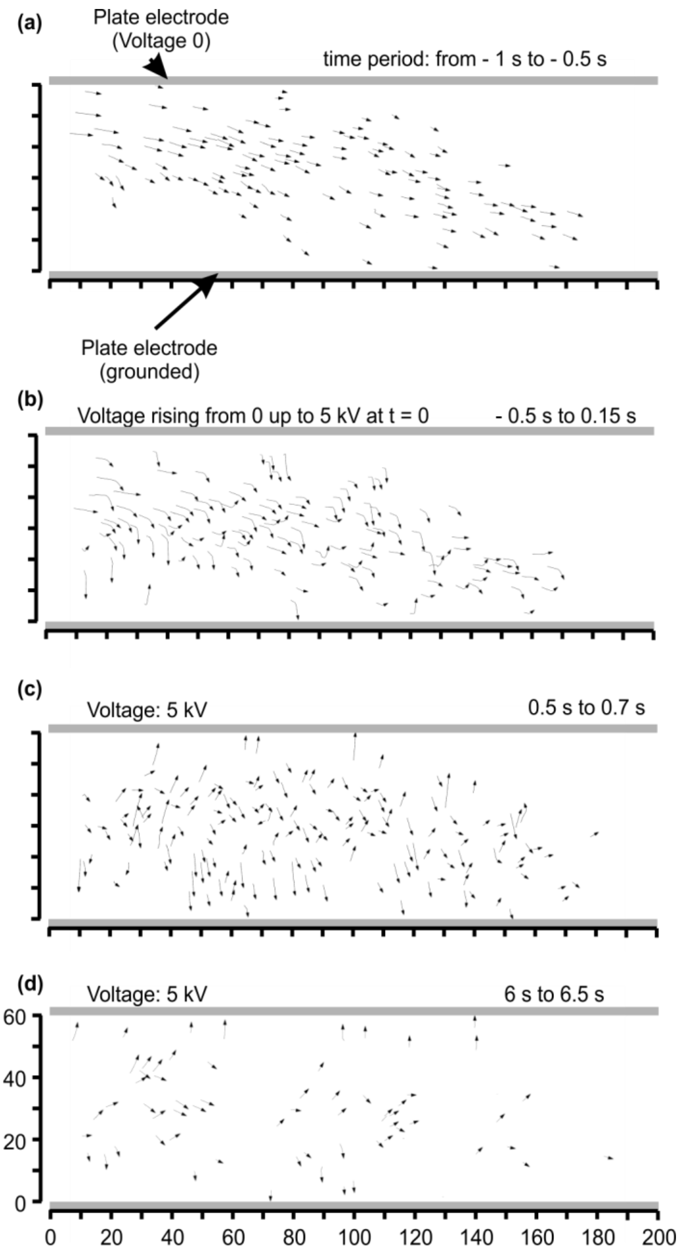

Fig. 4. Movement trajecitries of the microparticles in the space between two plate electrodes. The voltage of 5 kV was applied to the top electrode in time t = 0.

At first (Fig. 4 a), the microparticles flow horizontally in the direction of the EHD air flow generated by the SDBD actuator. A slight descent of the particles is due to gravitation force (density of the aluminum oxide particles is about 10^3 larger compared to air). After applying the voltage (+ 5 kV) to the electrodes (Fig. 4 b) at time t = 0 the horizontal movement of the particles was disturbed. The Al_2O_3 microparticles, charged either positively or negatively, were subjected to the electric field existing between the two plates. In consequence, the positively and negatively charged Al_2O_3 microparticles undergo separation of direction of movement (Fig. 4 b,c). The positively charged Al_2O_3 moved to the grounded electrode (the lower), the negatively polarized ones went to the positively stressed electrode (the upper). The velocity of the charged particles in the vertical direction reaches up to 150 mm/s. The movement of a few, not charged particles was undisturbed by the electric field as they continue to move horizontally. As the charged particle reach one of the electrodes it settles its surface. Thus the effect of electrostatic precipitation of the charged trace microparticles occurs. It can be noticed that about 15% more of the charged particles travels in the direction of grounded electrode. Such a behavior can be understood if we consider that a net charge of the particles is slightly positive [16]. This inequality is due to higher mobility of negative charges than positive. Within the elapsing time most of the charged particles have settled on the electrodes and in the flow remains only natural and weakly charger particles (Fig. d).

The result of the microparticle tracking shows that the Al_2O_3 particles introduced into the EHD air flow generated by the SDBD are charged of both polarities. This indirectly confirms the presence of both positive and negative charged species in the EHD air flow (the negative species were not observed using the optical emission spectroscopy method).

IV. Conclusions

In this paper we presented the results of the experiments on the gaseous charged species produced in the surface dielectric barrier discharge using the optical emission spectroscopy and particle tracking methods. The spectroscopy experiments shown that the plasma spectrum is dominated by the second positive band of N_2. The first positive band of N_2^+, NO and OH, as well as the atomic lines of O were also found in plasma spectrum. It was directly concluded that the dominant positive charge carrier in the SDBD was the N_2^+. In the second experiment a microparticles made of aluminum oxide were introduced into the EHD air flow generated by the SDBD and the trajectories of the particles in the external electric field were determined. We observed the separation of direction of movement of the microparticles in the electric field. The particles moved according or contrary to the electric field lines. This indirectly confirmed the presence of charged species of both polarities in the EHD air flow.

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References

[1] N. Bernard, and E. Moreau, " Electrical and mechanical characteristics of surface AC dielectric barrier discharge plasma actuators applied to airflow control", Exp. Fluids, vol. 55, pp.1846, 2014

[2] J.J. Wang, W. Choi, L.H. Feng, T. N. Jukes, and R. D. Whalley, "Recent developments in DBD plasma flow control", Prog. Aero. Sci., vol. 62, pp. 52-78, 2013

[3] G. Borcia, C.A. Anderson, and N.M.D Brown, "Using a nitrogen dielectric barrier discharge for surface treatment", Plasm. Sor. Sci. Tech., vol. 14, pp. 254-267, 2005

[4] I Adamovich et al., "The 2017 plasma roadmap: low temperature plasma science and technology", J.Phys. D Appl. Phys., vol. 50, pp. 323001, 2017

[5] K.G. Kostov, V. Rocha, C.Y. Koga-Ito, B.M. Matos, M.A. Algatti, R.Y. Honda, M.E. Kayama, and R.P. Mota, "Bacterial sterilization by a dielectric barrier discharge (DBD) in air", Surf. Coat. Tech., vol. 204, pp. 2954-2959, 2010

[6] Y. Li, R. Yi, C. Yi, B. Zhou, and H. Wang, " Research on the degradation mechanism of pyridine in drinking water by dielectric barrier discharge", J. Env. Sci., vol. 53, pp. 238-247, 2017

[7] E.Moreau, A. Debien, N. Bernard, T. Jukes, R. Whalley, K.S. Choi, A. Berendt, J. Podlinski, and J. Mizeraczyk, "Surface dielectric barier discharge plasma actuators", ERCOFTAC Bulletin, vol. 94, pp. 5-10, 2013

[8] R. J. Adrian, Particle Image Velocimetry, Cambridge University Press, 2011, pp. 18-28

[9] NIST National Institute of Standards and Technology Database

[10] B. Eliasson, and U. Kogelschatz, "Electron impact dissociation in oxygen", J. Phys. B: At. Mol. Phys., vol. 19, pp. 1241-1246, 1986

[11] D. Nie, W. Wang, D. Yang, H. SHi, Y, Huo, and L. Dai, " Optical study of diffuse bi-directional nanosecond pulsed dielectric barrier discharge in nitrogen", Spec. Act. A Mol. Bio. Spec., vol. 79, pp. 1896-1903, 2011

[12] W. Linsheng, P. Bangfa, L. Ming, Z. Yafang, and H. Zhaoji, "Dynamic characteristics of positive pulsed dielectric barrier discharge for ozone generation in air", Plasm. Sci. Tech., vol. 18, pp. 147-156, 2016

[13] M. Benyamina, A. Belasri, and A. Khodja, "Physicochemical investigation of homogeneous pulsed discharge in N2/O2 for ozone production", vol. 36, pp. 253-263, 2014

[14] M.J. Pinheiro, and A.A. Martins, " Electrical and kinetic model of an atmospheric RF device for plasma aerodynamics applications", J. Appl. Phys., vol. 108, pp. 033301, 2009

[15] J.P. Borra, "Charging of aerosol and nucleation in atmospheric pressure electrical discharges", Plas. Phys. Coll. Fus., vol. 50, pp. 124036, 2008

[16] N. Jidenko, E. Bourgeois, and J.P. Borra, " Aerosol charge distributions in dielectric barrier discharges", Proc. of. European Aerosol Conference, 2009