Properties of the coaxial DBD forming plasma jet in the air flow at atmospheric pressure

Yu S Akishev\textsuperscript{1,2*}, G I Aponin\textsuperscript{1}, A A Balakirev\textsuperscript{1}, V B Karalnik\textsuperscript{1}, A V Petryakov\textsuperscript{1} and N I Trushkin\textsuperscript{1}

1 SRC RF TRINITI, 108840, Moscow, Troitsk, Pushkovykh street, 12, Russia
2 NRNU MEPhI, 115409, Moscow, Kashirskoe shosse, 31, Russia

*akishev@triniti.ru

Abstract. The non-thermal plasma source based on the high-frequency (100 kHz) sinusoidal dielectric barrier discharge (DBD) generating the plasma jet in air at atmospheric pressure is described. This source uses the electrode system of a coaxial geometry and able to work at the low- and high-power regimes. The features of DBD in these regimes are discussed. A narrow plasma jet was generated in airflow at the velocities in the range of 20-80 m/s. The presented experimental results give insight into the spatial-temporal behaviour of the gas discharge plasma inside the coaxial DBD and the spatial characteristics of plasma jet outside the discharge zone as well.

1. Introduction
Non-thermal plasma (NTP) generated by discharges in gas glow at atmospheric pressure is widely used for many applications [1-13]. Along with gas discharges, electron beams of moderate and high energy are also used for the NTP generation [14-16]. In most cases, plasma jets are being formed by discharges in the flow of the inert gases (He, Ar, N\textsubscript{2} and their mixtures) as work gases. The ambient air contains the electronegative components (oxygen and water molecules) which are able to efficiently quench electronically excited species and, besides, they diminish the concentration of electrons in plasma due to strong attachment processes. This circumstance leads to diminishing of the concentration of reactive species and shortening of the action range of these species in air plasma jet. Therefore there was always a strong doubt - whether the plasma jet in ambient air can provide the concentration of reactive species which is sufficient for effective plasma processing. On the other hand, atmospheric pressure air plasma jets are of great interest because the replacement of the expensive inert gases by the ambient air promises a high profit for the plasma-based technologies.

In this paper, we present the newly developed gas discharge system generating plasma jet using the ambient air as working gas at atmospheric pressure. This system is based on the usage of the coaxial high-frequency (100 kHz) sinusoidal DBD in fast flow velocity (20-80 m/s) of the ambient air with a high volume flow rate of 4-24 L/min. High flow velocity provides faster delivering of reactive species from discharge zone to the surface that reduces their loss due to the quenching or other plasma-chemical processes in the jet and increases the total amount of the delivered reactive species onto the surface to be treated. The latter leads to the intensification of the plasma surface processing. We used a high-voltage sinusoidal power supply with a frequency of 100 kHz and output power about 1 kW. Note that high-frequency DBD is able to provide a high specific energy deposition into the working gas. Due to fast quenching processes at atmospheric pressure, it leads to strong air heating that, in its
turn, can lead to a positive synergy effect of the simultaneous action of hot air and reactive plasma species at the surface treatment.

2. Experimental setup

General scheme of the single-tube reactor is shown in figure 1. Note the coaxial electrode system was never applied before for plasma jet generation in the ambient air as working gas. The main feature of this system is that the inner HV pin electrode was wholly located outside the zone enclasped by the outer cylindrical electrode. This feature allowed us to increase both the volume of discharge zone in the tube and the residence time of gas being activated by the discharge.

![Figure 1](image)

**Figure 1** Setup of the coaxial DBD in fast air flow at atmospheric pressure. The inner and outer diameters of the dielectric tube are 2 and 4.5 mm. The length of discharge zone is 20 mm.

The applied high voltage was measured by HV divider PINTEK HVP-39 (1000:1, 40 kV, 200 MHz). The discharge current was measured by a low-inductive shunt with resistance of 50 Ohm. All electrical signals were recorded by the digital oscilloscopes such as Tektronix TDS 520, Tektronix DPO2024 and Tektronix TDS 2012 with bandwidth of 500, 200 and 100 MHz. The current and voltage waveforms were used to calculate the average discharge power $<W>$:

$$<W> = \frac{1}{nT} \int_0^{nT} I(t)U(t)dt,$$

where $I(t)$ and $U(t)$ are the current and voltage waveforms of the sinusoidal DBD recorded in the experiment by the digital oscilloscope, $n$ is the number of periods $T$ taken into consideration.

The discharge and plasma jet images were taken by digital camera Canon EOS 550 with the exposure time down to 10^{-4}s and multi-frame fast camera (equipped with the intensifier) with the exposure time down to 50 ns. The concrete exposure time has been determined by both the light intensity of the registered discharge and plasma jet and the sensitivity of the used optical device.

The barrier discharge was generated in the airflow inside thin quartz or ceramic tube. The sizes of tubes were chosen close to each other as much as possible. The inner and outer diameters of the quartz and ceramic tubes are of 2.0 and 4.5 mm and 2.5 and 4.5 mm, respectively. At given inner diameters of tubes and gas flow velocities (20-80 m/s) Reynolds number of flows inside tubes exceeds the critical number $Re \approx 2320$. It means that flow of the ambient air inside tubes is turbulent one.

3. Experimental results and discussion

The images in figure 2 show the evolution of the plasma structure inside the discharge zone at the increasing the amplitude $U$ of the applied sinusoidal voltage. These images are averaged over many half-cycles. The current-voltage waveforms of the airflow DBD in the regimes corresponding to the discharge photos at $U = 4.5$ kV and $U = 7.6$ kV is shown in figure 3.

One may see in figure 2 that the discharge strongly changes its structure at the increase in the amplitude $U$, i.e. the discharge occupies the larger volume at higher voltage. These changes in the spatial structure are accompanied by the essential changes in the discharge current waveform. Figure 3 presents these changes by the example of the low-power (LP) and high-power (HP) regimes. In the LP regime, the discharge current consists only of the high amplitude sharp peaks. In the HP regime, the current consists of two components: major component is the smoothly changing current and minor
component is the sharply changing current with peaks of low amplitude. The existence of the smoothly changing background current we attribute to the existence in each half-cycle of the survived plasma of high concentration (about $10^{12}$ cm$^{-3}$) generated in the previous half-cycle.

![Grounded electrode](image1.png) ![Grounded electrode](image2.png)
![HV electrode](image3.png) ![HV electrode](image4.png)

**Figure 2** The averaged in time images (side view) of DBD structure inside the quartz tube at different applied voltages. The length of discharge zone is 20 mm. Exposure time is 1 ms. $V = 60$ m/s. a) $U = 4.5$ kV, $<W> = 3.7$ W, b) 5.3 kV, $<W> = 6.4$ W, c) 7 kV, $<W> = 68.5$ W, d) 7.6 kV, $<W> = 86.3$ W.

![Current and voltage waveforms](image5.png)

**Figure 3** The current and voltage waveforms of the airflow DBD in the regimes corresponding to photos at $U = 4.5$ kV (a) and $U = 7.6$ kV (b) in figure 2 respectively.

Evolution of the visual length of the air plasma jet with changes of the airflow velocity $V$ is shown in figure 4. The visual information is complimented with data in figure 5. The dependence of the average discharge power $<W>$ on the applied voltage amplitude $U$ at the gas flow velocity $V = 60$ m/s is given in figure 5a. The dependence of visual length of plasma jet on $<W>$ and $V$ is depicted in figures 5b and 5c. The dotted arrows in figures 5a and 5b show a sharp DBD transition (like jump) from the low-power regime into high-power regime. The arrow in figure 5c shows the termination of DBD if the velocity exceeds the critical magnitude about of 75 m/s. It was observed also that airflow DBD in the low-power regime generates ozone but transition into the high-power regime terminates the ozone production.
Figure 4 The visual length of the air plasma jet vs the airflow velocity \( V \). Exposure time of each photo is 3 s, \( U = 5.5 \) kV. a) 20 m/s, 8W; b) 30 m/s, 65.2W; c) 50 m/s, 53 W; d) 75 m/s, 10.7 W

Figure 5 (a) The dependence of \( <W> \) vs \( U \) at the gas flow velocity \( V = 60 \) m/s. The visual length of the air plasma jet vs the average discharge power \( <W> \) (b) and vs gas velocity \( V \) at \( U = 5.5 \) kV (c). The squares and circle correspond to ceramic and quartz tube. The arrows in (a) and (b) show the sharp transition of DBD from the low- to high-power regime; arrow in (c) shows the termination of DBD at higher \( V \).
Figure 6. Images of the discharge zone and plasma jet taken with a short exposure time. The instant images are correlated with the proper $I$-$U$ waveforms placed below the pictures. High voltage was applied to outer electrode. $V = 60$ m/s, high-power regime $< W > \approx 75$ W. The exposure time of the discharge zone is 100 ns and plasma jet 1.0 $\mu$s (window A) and 1.0 $\mu$s (window B). The figures show the position of the shots on the time axis.

It is interesting to trace in detail the evolution of plasma structure with high time resolution. Such information is presented in figure 6. Note that the brightness of the discharge zone inside tube strongly exceeds the brightness of the plasma jet. In fact, the dim air plasma jet is hardly visible with the naked eye. Therefore the “bright” plasma jet depicted in figure 4 is the trick which was obtained due to the chosen exposure time for plasma jet. This exposure time was much longer compared to that for the discharge zone. Besides, figure 4 shows the images averaged over long time but figures 6a and 6b show the instant images of the discharge zone at positive and negative phases of the discharge current. Note that the propagation of so-called “plasma bullets” along hot air plasma jet outside the tube was not observed.

4. Conclusion
We have developed novel plasma source of the "efflux" type that is based on the usage of the coaxial high-frequency (100 kHz) sinusoidal DBD in fast flow velocity (20-80 m/s) of the ambient air with a high volume flow rate of 4-24 L/min per tube. The configuration electrode and gas-dynamic and electrical regimes were never been used before for generation of plasma jet in the ambient air as working gas at atmospheric pressure. The usage of high-frequency voltage allows one to increase appreciably the specific energy deposition in the discharge and to heat the airflow up to the high temperature of 500-600 C. We have revealed two regimes (low-power and high-power) of airflow DBD and determined the existence of upper limit of gas flow velocity that terminates the work of DBD. Our findings promote more insight into physics of the airflow DBD at atmospheric pressure.

Acknowledgement
This work was supported by the RFBR. Grants No 17-02-00234, No 18-02-00539.

References
[1] Kim M C, Yang S H, Boob J H and Han J G 2003 Surf. Coat. Technol. 174-175 839
[2] Laroussi M and Lu X 2005 Appl. Phys. Lett. 87 113902
[3] Temmerman E, Aksishev Yu, Trushkin N, Leys C and Verschuren J 2005 J. Phys. D: Appl. Phys. 38 505
[4] Winter J, Brandenburg R, and Weltmann K D 2014 Plasma Sources Sci. Technol. 24 064001
[5] Korolev Y 2015 Russ. J. Gen. Chem. 85 1311
[6] Akishev Yu, Grushin M, Dyatko N, Kochetov I, Napartovich A, Trushkin N, Duc T and Descours S 2008 J. Phys. D: Appl. Phys. 41 23520
[7] Babaeva N Y and Kushner M J 2014 Plasma Sources Sci. Technol. 23 015207
[8] Sosnin E A, Panarin V A, Skakun V S, Baksht E K and Tarasenko V F 2017 Eur. Phys. J. D 74 25
[9] Lu X, Naidis G V, Laroussi M, Reuter S, Graves D B and Ostrikov K 2016 Phys. Rep. 630 1
[10] Akishev Yu S, Grushin M, Karalnik V, Petryakov A and Trushkin N 2012 IEEE Trans. Plasma Sci. 40 2806
[11] Bartis E A, Graves D B, Seog J and Oehrlein G S 2013 J. Phys. D: Appl. Phys. 46 312002
[12] Akishev Yu, Balakirev A, Grushin M, Kochetov I, Napartovich A, Petryakov A and Trushkin N 2015 IEEE Trans. Plasma Sci. 43 745
[13] Korolev Y D, Frants O B, Geyman V G, Landl N V and Kasyanov V S 2011 IEEE Trans. Plasma Sci. 39 3319
[14] Akishev Yu S, Karal’nik V B, Petryakov A V, Starostin A N, Trushkin N I and Filippov A V 2016 Plasma Phys. Rep. 42 14
[15] Akishev Yu S, Karal’nik V B, Petryakov A V, Starostin A N, Trushkin N I and Filippov A V 2017 J. Exp. Theor. Phys. 124 231
[16] Levko D, Krasik Y, Tarasenko V, Rybka D and Burachenko A 2013 J. Appl. Phys. 113 196101