A New DBD-driven Atmospheric Pressure Plasma Jet Source on Air or Nitrogen

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ABSTRACT

The paper proposes a new atmospheric pressure plasma jet (APPJ) source for operation in air and nitrogen. The conditions for the formation of stable plasma jets 4 cm long are determined. Energy and spectral measurement data are presented.

Keywords: plasma jet, atmospheric pressure, nitrogen, air

1. INTRODUCTION

Now, atmospheric pressure plasma jets (APPJs) are the subject of numerous studies[1-3] due to the prospects of their application in medicine[3-5], for inactivation of biological systems[3,6,7], and for surface treatment such cleaning, etching, thin film deposition[1,8-10], etc.

A plasma jet is formed in different types of discharge (glow, arc, RF, barrier, etc.) and is extracted through a narrow nozzle of round or slit cross-section due to excess pressure (higher than atmospheric) produced in the discharge zone. Glow, corona or dielectric barrier discharges (DBD) generate nonequilibrium plasma with an average gas temperature of 20–400 ^{0}C, charged particle density of 10^{11}–10^{12} cm^{-3}, and concentration of reactive species of 100 ppm. At temperatures close to room temperature, the plasma is termed cold atmospheric plasma or nonthermal plasma.

The DBD-driven APPJ sources available to date use He, Ar, N_2, air or inert gas mixtures with nitrogen or oxygen[3-15]. For the formation of plasma, use is made of positive and negative voltage pulses with a duration of ~0.1–1 μs, amplitude of 30 kV, and repetition frequency of tens of kilohertz at a gas flow rate from several to tens of liters per minute. In some cases, radio-frequency excitation is used [3,6].

Much less attention is paid to measurements of the APPJ energy characteristics and temperature, including the temperature profile over the jet cross-section. These measurements are particularly urgent for operating modes with gas temperatures greater than 100 ^{0}C, which is the case when inert gases are replaced by their mixtures containing electronegative molecular gas, air or nitrogen. These modes produce more chemically active particles[3,16] but require voltage higher than 15 kV. Moreover, with molecular gases, the plasma flow is more sensitive to the gas flow rate and its temperature increases. Hence, the plasma source can no longer be considered as nonthermal.

The aim of the present study is to excite a stable DBD-driven APPJ in air and nitrogen with a minimum gas flow rate of 1 l/min and to determine its energy, temperature, and spectral characteristics.

2. EXPERIMENTAL EQUIPMENT AND RESEARCH TECHNIQUES

A block diagram of the experimental setup is shown in Figure 1. The plasma jet was formed by a dielectric barrier discharge in quartz tube *1* with a nozzle diameter of 1.5 mm. Power supply *3* allowed us to vary the voltage pulse duration from 1 to 1.5 μs, pulse repetition frequency from 10 to 90 kHz, and voltage amplitude up to 13 kV.

The time dependence of voltage and current pulses on the tube was recorded with a Tektronix TDS 224 oscilloscope. A nitrogen or air flow was supplied in tube 1; the gas flow rate was controlled by flowmeter *6* (U/AR) and pressure sensor *5* (PSE 511, SMC Corp.) the signals from which were transmitted to oscilloscope *4*.

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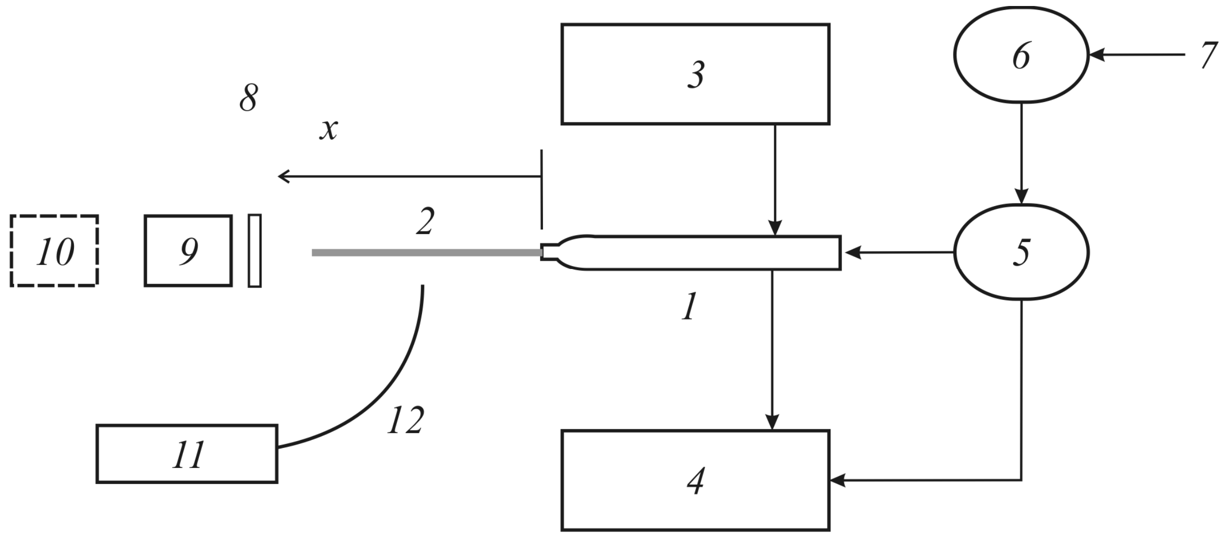

Figure 1. Block diagram of the experimental setup: *1* – APPJ source; *2* – APPJ; *3* – power supply; *4* – oscilloscope; *5* – pressure sensor; *6* – gas flow regulator; *7* – gas supply; *8* – quartz plate; *9* – photodetector; *10* – thermoelectric converter; *11* – spectrometer; *12* – optical fiber; *x* – distance from the nozzle to a measurement point.

The APPS radiant power was measured using photodetector *9* (HAMAMATSU H8025-222) with a maximum spectral sensitivity at λ = 222 nm which was placed on the plasma flow axis at different distances x. The input window of the photodetector was insulated from the plasma jet heat with quartz plate 8. For temperature measurements, the photodetector was replaced by thermocouple *10* (OPC 011-0.5/3) with a heat regulator (TRM202).

The plasma jet emission spectrum was recorded using optical fiber *12* of known bandwidth the signal from which was transmitted to a spectrometer (Ocean Optics HR2000+ES).

3. RESULTS AND DISCUSSION

Our preliminary experiments were performed on an APPJ source similar in design to that described elsewhere[17,18]. The experiments allowed us to obtain an APPJ in helium and argon, but the formation of a plasma jet in air or nitrogen failed: the discharge was kept inside tube *1* (Figure 1) and no plasma jet was formed even at a gas flow rate of 30 l/min.

Therefore, a new plasma source differing in design from the available sources[17,18] was proposed and tested (Figure 2). The difference is that at the inner surface of the cylindrical tube inlet there is electrode *5* connected coaxially with pin electrode *6* inserted into nozzle *7*. The dimensions of the tube sections (lengths L_1, L_2, radii r_1, r_2,) and the dielectric constant (ε) are such that the capacitance of its inlet (C_{in}) is much higher than that of its outlet (C_{out}).

The plasma formation directly at the nozzle minimizes the loss of chemically active particles at the walls of the device. The condition $C_{in} >> C_{out}$ makes the voltage steeper, i.e., decreases the voltage pulse rise time and increases its amplitude in the discharge region, which is required for gas discharge devices operated at increased pressures of gas media containing electronegative gases, nitrogen or air.

The design ensured the formation of an APPJ in air and nitrogen. After the discharge ignition, up to 30 s was required to attain stable discharge operation (Figure 3). The jet diameter was normally no greater than 0.5–1 mm. At an optimum gas flow rate of g = 0.5 l/min, pulse duration of τ = 1–1.5 μs, repetition frequency of f = 45–85 kHz, and voltage amplitude of up to 13 kV, we managed to obtain a jet of length ~3 and 4 cm in air and nitrogen, respectively. At a gas flow rate lower than 0.05 and higher than 10 l/min, no plasma jet was formed or the jet length was about a mere 1 mm; that is the optimum gas flow rate g ~ 0.5 l/min was noticeably lower than those reported previously.

The APPJ emission spectrum in nitrogen and air at a wavelength of 280–450 nm contains electron-vibrational bands of the first positive nitrogen system $C^3\Pi_u \rightarrow B^3\Pi_g$ with characteristic peaks at wavelengths of 296 (3, 1); 315 (1, 0);

337 (0, 0); 353 (1, 2); 357 (0, 1); 375 (1, 3); 380 (0, 2); 400 (1, 4); 406 nm (0, 3); the numerals in brackets are the vibrational numbers v', v'' corresponding to the transitions.

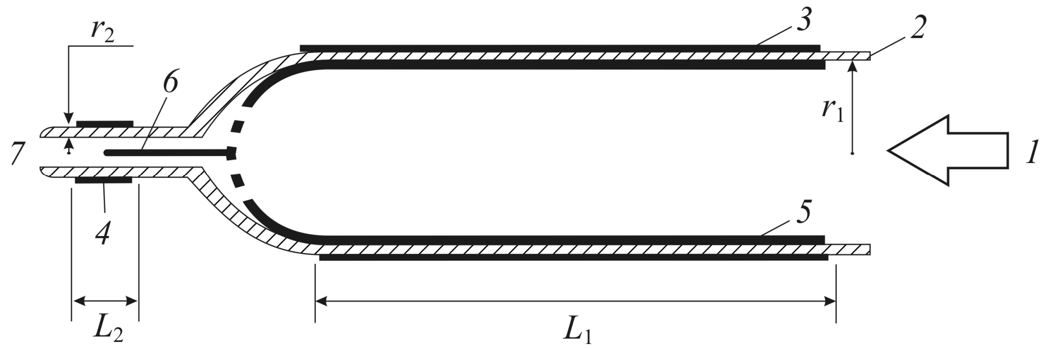

Figure 2. Block diagram of the APPJ source: *1* – gas supply; *2* – dielectric tube; *3*, *4* – spaced outer electrodes of the tube; *5*, *6* – inner electrode consisting of cylindrical electrode *5* and pin electrode *6*; *7* – nozzle for plasma jet extraction.

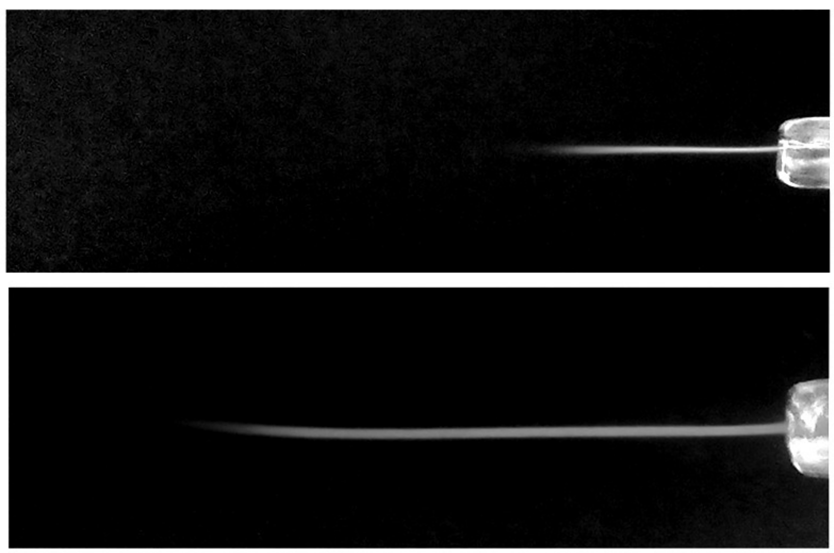

Figure 3. Plasma jet in air within 10 s (top) and 20 s (bottom) after the ignition at f = 75 kHz; the image width at the base is 4 cm.

Figure 4 presents measurement data on the ultraviolet radiant exitance of the plasma jet in the axial direction at different distances for nitrogen and air. It is seen that under the same conditions, the APPS radiant exitance in air is about twice as much as that in nitrogen.

According to the data in Figure 4, the plasma jet is similar to a point source through the entire length (in the x direction). At this rate, the plasma jet UV radiant power can be expressed as

$$P \approx \frac{4\pi P_{UV}}{S_f} l\{l + L\}, \qquad (1)$$

where P_{UV} is the radiant exitance at the photodetector; S_f is the light-sensitive element square of the photodetector, l is the plasma jet length; L is the distance between the plasma jet end and photodetector. Equation (1) is valid because the plasma jet radius is $r_0 << L$ and $r_0 << l$ [19]. Then, according to (1), the total UV radiant power of the APPJ flow in nitrogen and air for the conditions of Figure 4 is ~ 0.3 and 0.5 W, respectively.

Figure 5 shows temperature dependences of a plasma jet of length 40 mm on its axis at different distances from the nozzle for nitrogen and air. It is seen that in both gases, the plasma jet temperature depends linearly on the distance from the nozzle.

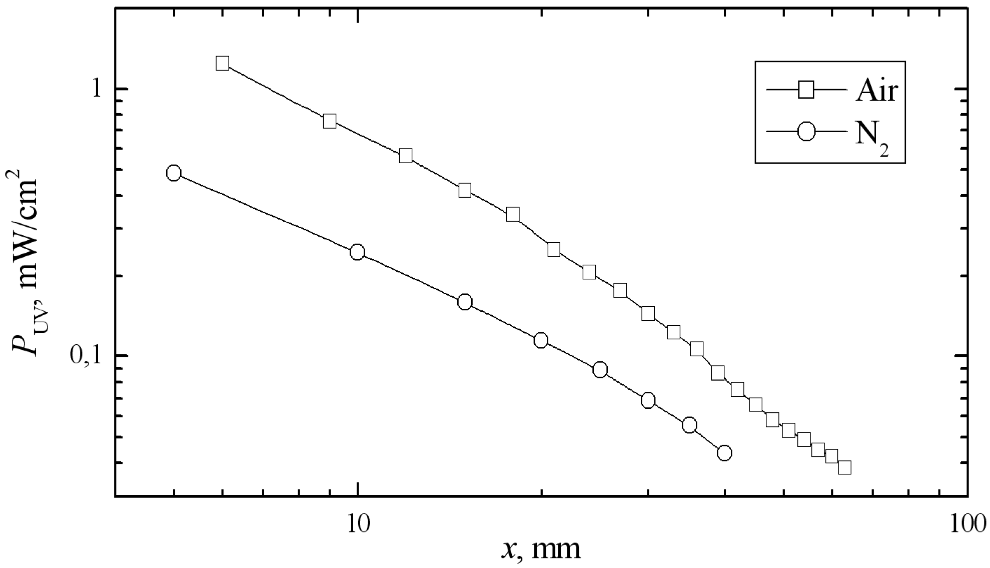

Figure 4. APPJ radiant exitance in the axial plasma jet direction at different distances from the nozzle for air and nitrogen at $f = 86$ kHz, $\tau = 1$ μs, $g = 0.5$ l/min.

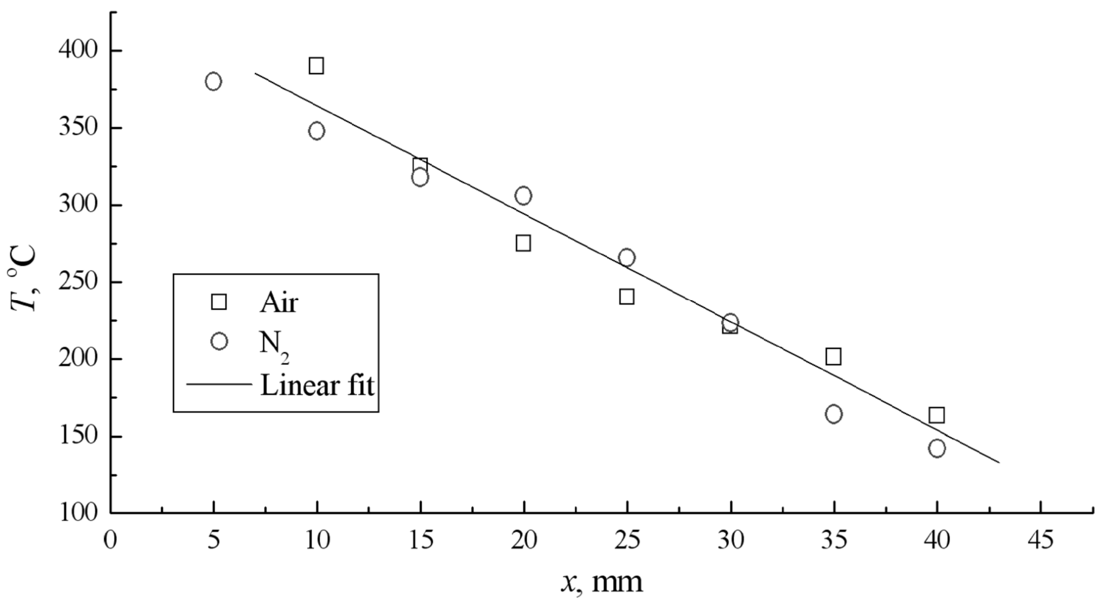

Figure 5. Plasma jet temperature at different distances from the nozzle for air (□) and nitrogen (○) at $f = 86$ kHz, $\tau = 1$ μs, $g = 0.5$ l/min; the straight line corresponds to linear approximation.

Thus, the new APPJ source offers a combination of characteristics typical for plasma jets in glow, corona, and barrier discharge at an average gas temperature of 20–400 ^{0}C, while not requiring high initiating and operating voltages and/or high gas flow rates ($g \geq 10$ l/min). The resulting plasma jets are stable both in nitrogen and in air under normal conditions, though the gas flow rate is low ($g > 5$ l/min).

4. CONCLUSION

The new source of stable plasma jets in atmospheric pressure air and nitrogen was developed. It is shown that in a barrier discharge with a minimum gas flow rate of $g \sim 0.5$ l/min, pulse duration of $\tau = 1–1.5$ μs, repetition frequency of $f = 65–85$ kHz, and voltage amplitude of up to 13 kV, plasma jets of typical diameter no more than 0.5–1 mm and length up to ~ 3 and 4 cm are formed in air and nitrogen, respectively.

The APPJ emission spectrum at 280–450 nm is hardly dependent on the working gas and is dominated by the first positive nitrogen system. The APPJ UV radiant power in nitrogen and air is ~ 0.3 and 0.5 W, respectively. In the new source, the plasma jet temperature along the jet axis depends linearly on the distance from the nozzle.

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