Atmospheric pressure air plasma jet from microdischarge in porous ceramics

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Abstract: Ambient temperature atmospheric pressure plasma jet is generated by microdischarge in Ar, N₂ or air flowing through porous ceramic disk inserted between two metal disk electrodes with holes at the center for gas passage. The electrical power dissipated for the discharge is less than 5 W when 60 Hz AC is used as the power source. The electron temperature and the electron number are estimated to be 1.3 eV and 7.5×10¹¹/cm³, respectively. Emission spectra show that excited species, such as O, OH, and N₂⁺ are present in the air plasma jet and the analysis of the N₂ lines reveals that the vibrational and the rotational temperature are 4000 K and in the range of 300-330 K, respectively. Such simple device capable of generating the air plasma jet will have great potential use in many applications related to surface treatments.

Keywords: Atmospheric pressure air plasma, microplasma in porous ceramics, plasma jet

1. Introduction

Atmospheric pressure, non-equilibrium microplasmas have become powerful experimental tools for many applications in areas such as microfabrications in microelectronics [1], surface modifications [2], light sources [3-5], and environmental processing [6] – to name just a few. The wide range of applications of the microdischarge is attributed to the merits of excluding vacuum equipments in the processes and generating spatially confined high electron density plasmas using small electrical power [7]. Microdischarges operational in atmospheric pressure air are particularly attractive and such discharges now can be generated employing electrode configurations such as micro-hollow cathode (MHC) [4], capillary plasma electrode [7], microporous ceramics [6,8], microstrips [9], electrodes with dielectric barriers [10], and a cylindrical anode-flat cathode [11].

For some applications, particularly for polymer-surface treatments, sterilization of disease germs and biomedical treatments, it is desired to convert the microplasma into a jet or plume by providing a gas nozzle or passage. For such applications the temperature of the jet should be sufficiently low not to damage the object surface to be treated. The temperature of the plasma is closely related to the carrier gas used and in this regard inert gas like He or Ar is the usual gas of choice. Use of the inert gases is particularly useful as the distance between electrodes gets longer to avoid plasma instability due to glow-to-arc transition (GAT). The temperature of the jet can be further lowered by use of the power provided in the form of very short pulses [12,13].

In our previous work [14], we investigated nitrogen microplasma jets at atmospheric pressure produced using micro-hollow discharge powered by 20 kHz AC source. The aluminum disk electrodes and the dielectric disk (made of Teflon, glass or quartz) used in the device have holes of 500μm diameter at the centers. As nitrogen gas was allowed to flow through the aligned holes of the electrode-dielectric assembly to which the AC power was applied, a long plasma jet of over 6 cm long was formed in front of the front electrode. The device was operational for many hours ejecting a stable plasma jet into open air. When air was used instead of nitrogen gas the performance of the device did not change much. But the nitrogen plasma jet showed a long-term effect to the device by causing some degree of structural damage inflicted around the hole of the dielectric disk. The burning around the wall of the hole is believed to be caused by local heating of the disk wall when the electrical power dissipation is concentrated on a very small region near the aligned holes.

To circumvent this problem we adopted different discharge mode, namely, the microdischarge inside porous ceramics, for the plasma jet device. In this electrode configuration the discharge is not concentrated on the narrow region around the micro-hollow hole, but spread along the entire region of the porous ceramic disk. This type of discharge has the nature of the so-called back-
corona discharge. And adopting this type of discharge lifts the restriction on the diameter of the hole for gas passage since the electron pendulum motion inside the hole is no longer necessary for the ionization. In this work, we present a plasma jet produced by microdischarges in porous ceramics with some of its discharge characteristics. The device operational with the use of atmospheric pressure air powered by 60 Hz AC source is easy to use and capable of producing a long cold plasma jet of several centimeters. It is expected that it might be useful in treating thermally sensitive materials and in sterilization.

2. Experimental

Figure 1(a) and (b) show the experimental arrangement for the plasma jet device and the details of the electrode-porous dielectric disk assembly, respectively. The 60 Hz AC power supply is made of slidacs and transformer of 1:1000 turn ratio. The aluminum (Al) disk electrodes of 8 mm in diameter have holes of 1.5 mm diameter at the center for the air passage. Porous alumina disk (Al₂O₃, 99% purity, average pore size of 100 μm), 4 mm thick and 13 mm in diameter, was placed as a spacer between the Al electrodes. The exposed surface of the alumina disk, not covered with the Al electrodes, was covered with teflon so that no air leaked out from the surface. To prevent an electrical shock and damage caused by accidental contact of human body to the electrodes, the whole assembly was covered with teflon case and cap, as shown in Fig. 1(a).

All of the electrical measurements were made using a Tektronix oscilloscope (TDS 220, 100 MHz), a high-voltage probe (P6015A) and a current probe (A6303). The emission spectra were taken for 300–800 nm ranges along the slot length using a spectrometer (Acton 500, gratings 2400gr/mm with the resolution of 0.025nm) and a CCD (Andor DV-401) camera.

3. Results and Discussion

The plasma jet generated by the device was very stable and sustained for many hours. Its extended length out of the gas exit point at the front electrode seemed to depend largely on the applied voltage and the air flow rate. The gas flow also provided an effective cooling for the device. For example, this cooling effect due to the air flow at the rate was about 7.5 lpm made it possible to use easily machineable electrode materials such as aluminum. Under these conditions, we were able to operate the jet device for a week, a few hours of operation everyday, without any changes in the electrical discharge parameters.

Fig. 2(a)–(c) show the photographs of the plasma jet when air, N₂, or Ar gas was used as the carrier gas with the flow rate set at 7.5 lpm. The N₂ and Ar microplasma jet extended from the opening up to 45 and 30 mm, respectively while the air jet was relatively much shorter.

The gas temperature of the flame was simply measured using a thermocouple. The temperature of the plasma jet at a site 1 mm from the opening of the device was only 327 K, when the applied voltage was 4.2 kV<sub>rms</sub>. As can be seen in Fig. 2(d), the temperature of the plasma jet decreased with increase of the applied voltage V<sub>rms</sub>. Also the N₂ plasma registered the highest temperature at a given voltage among the three type of gases. The power dissipation was lowest with Ar gas at a given voltage when other conditions were all fixed for each gas. Also the mean discharge current and the dissipated power decreased with increase of the voltage.
The air plasma jet has however many advantageous features including production of a large amount of chemically reactive oxygen atoms, high tolerance to reactive gases, and low capital cost. The ionized air gas coming out of the device into ambient air can transfer its energy to the surrounding oxygen and nitrogen molecules, creating species such as O, OH, N₂⁺, etc. The length of the air plasma jet was about 15 mm at 4.2 kVrms of the voltage.

Fig. 2. Photographs of the jet when (a) air, (b) N₂ gas, or (c) Ar gas was used as the carrier gas and (d) shows the corresponding gas temperature.

The electron temperature $T_e$ can be roughly calculated using Einstein’s equation and swarm parameters of electrons in air

$$k_B T_e/e = D_e/\mu_e$$  \hspace{1cm} (1)

where $\mu_e$, $k_B$, and $D_e$ are the electron mobility, Boltzmann constant, electron diffusion constant, which is expressed as a function of $E/N$. From Fig. 2, the electric field $E$ is estimated to be 10.5 kV/cm, for the gap of 4 mm, showing $E/N=3.91 \times 10^{-16}$ V cm² for $N=2.687 \times 10^{19}$/cm³. The ratio of the diffusion coefficient to the electron mobility is calculated to be $D_e/\mu_e=1.33$ V for $E/N=3.91 \times 10^{-16}$ V cm² in dry air [15]. Thus the electron temperature is estimated to be about 1.3 eV.

The averaged electron density ($n_e$) can also be estimated from the equation

$$n_e = J/\left(E\mu_e\right)$$ \hspace{1cm} (2)

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consider that for air plasma at one atm, the electron mobility $\mu_e$ has a value of 714.3 cm$^2$/Vs from $\mu_e = 5.43\times10^5$ cm$^2$/Torr/Vs [15]. The current density $J$ is about 0.91 A/cm$^2$ by considering the effective discharge radius between the electrodes. Eventually, the peak electron density is estimated to be $7.5\times10^{11}$/cm$^3$.

Fig. 4(a) shows a representative optical emission spectrum (OES) of the air plasma when the power was fixed at 5 W. The spectrum was obtained by scanning from 200 to 900 nm mainly to include the $N_2$ second positive band, $C^3\Pi_u$-$B^3\Pi_g$, and the $N_2$ first positive band, $B^3\Pi_l$-$A^3\Sigma^+$. It also includes the characteristic lines of highly reactive radicals such as hydroxyl (OH) at 308.9 nm and atomic oxygen at 616 and 777.1 nm. The rotational and the vibrational temperature of the gas molecules under discharge was estimated by comparing the measured and simulated spectra (SPECAIR) of the $\Delta v$ = -2 transition from 367 nm to 380.4 nm of the second positive band ($C^3\Pi_u$ → $B^3\Pi_g$) of $N_2$ molecules as shown in Fig. 4(b). The best fit rotational ($T_R$) and the vibrational temperature ($T_v$) are about 320 K and 4000 K, respectively.

![Intensity vs Wavelength](image1)

**Fig. 4.** (a) The emission intensity of various lines of the $N_2$ in the discharge zone and (b) the measured and simulated emission spectra of the $\Delta v$ = -2 transition from 367 nm to 380.4 nm of the second positive band ($C^3\Pi_u$ → $B^3\Pi_g$) of $N_2$.

In conclusion, ambient temperature atmospheric pressure plasma jet was generated by microdischarge in Ar, $N_2$ or air flowing through porous ceramic disk sandwiched between two metal disk electrodes with holes at the center for gas passage. The electrical power dissipated for the discharge was less than 5 W when 60 Hz AC is used as the power source. The electron temperature and the electron number are estimated to be 1.3 eV and $7.5\times10^{11}$/cm$^3$, respectively. Emission spectra show that excited species, such as O, OH, and $N_2^+$ are present in the air plasma jet and the analysis of the $N_2$ lines reveals that the vibrational and the rotational temperature are 4000 K and in the range of 300-330 K, respectively. Such simple device capable of generating the air plasma jet will have great potential use in many applications related to surface treatments.

**References**