Atmospheric Pressure Nitrogen Microwave Plasma

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***Abstract*—We present nitrogen microwave blown-out plasma at atmospheric pressure and its emission spectra with their spatial distribution. The plasma had a symmetric conical shape until it collapsed to a funnel-like shape at high gas flow rates. We observed the emission of N_2, N_2^+, CN and NO: their Abel-inverted emissivity increased with increasing power and decreased with plasma radius.**

***Index Terms*—Atmospheric pressure, microwave plasma, nitrogen, optical emission spectroscopy.**

ATMOSPHERIC pressure microwave (MW) plasmas present considerable interest for a wide range of applications, such as air pollution control, surface treatment, or plasma synthesis. In this paper, we present the brief photographic and spectroscopic characteristics of atmospheric nitrogen MW torch plasma. We used a Litmas Red MW plasma torch (2.45 GHz, 3 kW) to generate atmospheric nitrogen plasma with temperatures 3000 K–4000 K. Contrary to the typical MW torch systems [1], gas in this paper was tangentially injected downwards at 45° or 60° from the vertical axis into the cylindrical MW cavity measuring 4 cm in diameter. The swirling plasma was then blown out vertically upwards through a conical nozzle 1 cm in exit diameter under 45° or 30° from the vertical axis. The experimental setup and basic torch characteristics were described in detail in [2]. We are currently testing the use of this plasma for waste carbon beneficiation.

Optical emission spectroscopy (emission spectrometer Ocean Optics SD2000, 200–1100 nm, optical system is described in [2]) and digital photography (digital SLR camera Canon EOS 300D) were used for diagnostics. We investigated the emission spectra of the blown-out MW plasma and dependence of the emission intensity and plasma shape on varying MW power and gas flow rate. Abel inversion was applied on the recorded line-integrated spectral profiles to obtain radial emissivity profiles providing the spatial distribution of the plasma emission.

We performed a series of experiments with MW power P varying from 0.97 to 1.78 kW at constant gas flow rate $Q = 15$ l/min. Plasma emission increased with increasing power, as shown in Fig. 1(a). The plasma shape remained conical at low Q and all P when a 45° nozzle was used. With a 30° nozzle (30° from the vertical axis) designed for higher Q, the plasma of some P collapsed into a funnel-like shape when Q reached a certain value (e.g., about 50 l/min at $P = 1.78$ kW), as shown in Fig. 1(b). This phenomenon is related to swirl gas flow properties inside the plasma cavity that propagate through the nozzle. At a 30° exit angle and high Q, thus high tangential velocity, the swirling plasma was strongly pushed toward the nozzle walls by a centrifugal force. This caused its funnel-like spread after exiting the nozzle. However, understanding the complex gas dynamic properties of the swirling plasma requires further research with modeling.

In the emission spectra, we identified N_2 molecules, N_2^+ ions and CN and NO radicals (Fig. 2). CN emission indicates the presence of carbon impurity in the feeding nitrogen gas. Stronger emissivity of N_2^+ (B-X) compared to N_2 (C-B) seems surprising because ionization of N_2 requires more energy than its excitation to the C state. In addition, N_2^+ (B) should not be formed by electron excitation, as generated plasma most probably does not contain electrons with such high energies ($\sim$19 eV). The N_2^+ (B) state is possibly formed by the reaction of N_2^+ (X) with vibrationally excited N_2 (X, v $>$ 11). N_2^+ (X) is formed by chemiionization via two metastable molecules N_2 (a′). This mechanism producing the so-called pink afterglow is further explained in [3].

Radial profiles of emission spectra at various heights h from the nozzle were recorded to study the spatial distribution of the species. These experiments were carried out at $Q = 15$ l/min and $P = 1.46$ kW. We measured the emission intensities in various horizontal positions from the vertical axis (radii r) with 1 mm spacing. We then applied Abel inversion to obtain radial emissivity profiles. We express the intensity (emissivity) in absolute units because the optical system was calibrated with radiation standards: W and D lamps. Radial emissivity profiles of N_2, N_2^+ and CN were radially symmetric and showed that the emissivity decreased with increasing r and h, except for the NO γ profile that was not symmetric, as shown in Fig. 3. We expected the strongest NO emission at the plasma edges, where heated nitrogen reacts with O_2 in the surrounding air and forms NO. However, we found the maximum emissivity in a certain r and not at the plasma edge. This is possibly because the plasma was spiral-twisted and entrained the surrounding air. It would also explain why the emissivity maximum was not found at the same radius for various heights.

These investigations revealed some basic tenets of physics and the spatial distribution of active species in the nitrogen atmospheric MW blown-out plasma that can be used for many applications.

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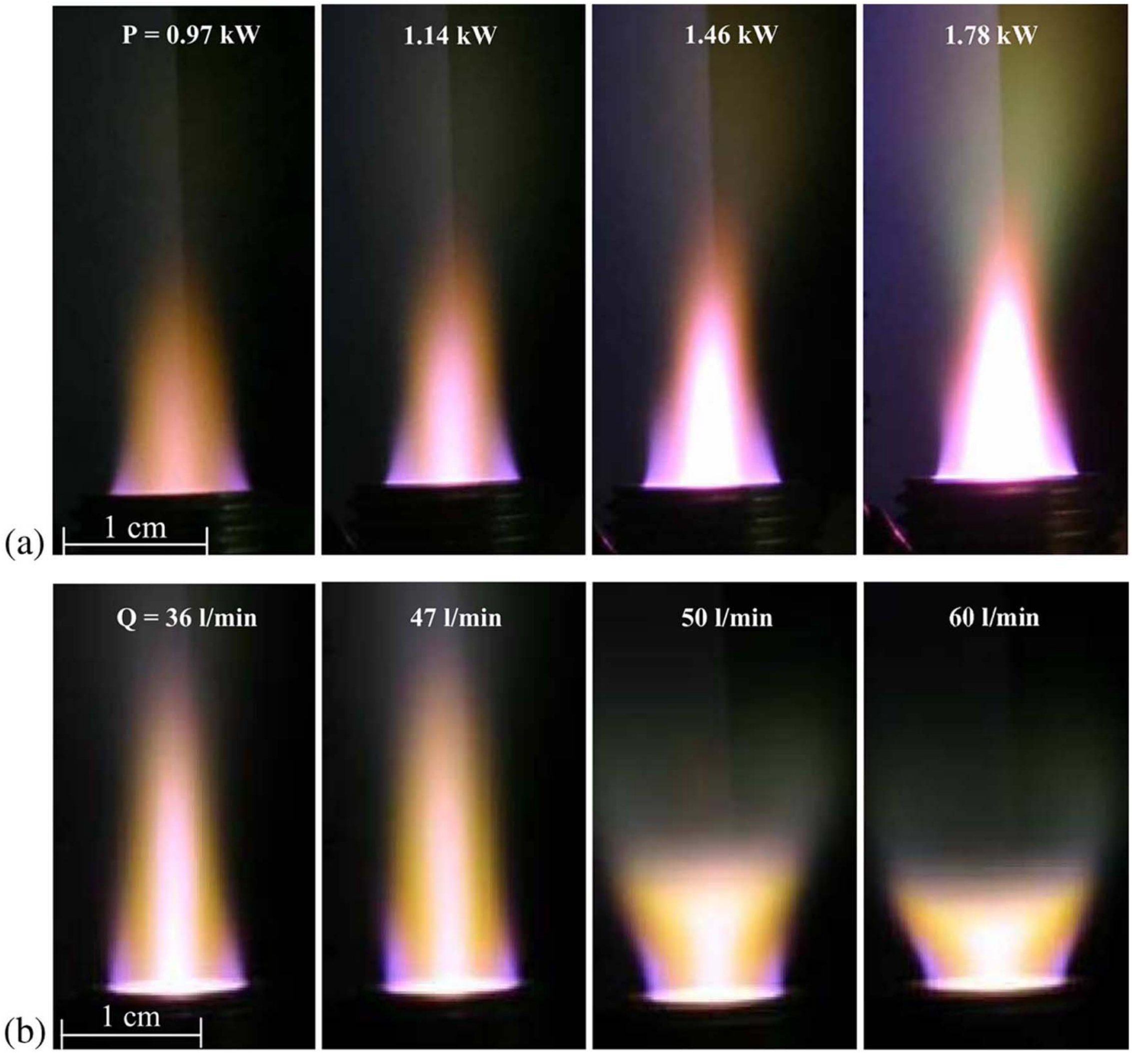

Fig. 1. Plasma photographs (a) at varying P with constant $Q = 15$ l/min (aperture 22, exposure time 2 s), and (b) a collapse of the plasma cone at higher gas flow rates ($P = 1.78$ kW, aperture 22, exposure time 1 s).

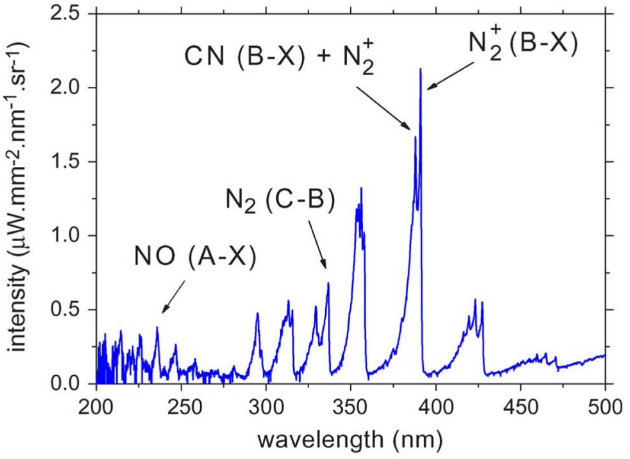

Fig. 2. Typical UV line-integrated emission spectrum of generated nitrogen MW plasma ($P = 1.46$ kW, $Q = 15$ l/min).

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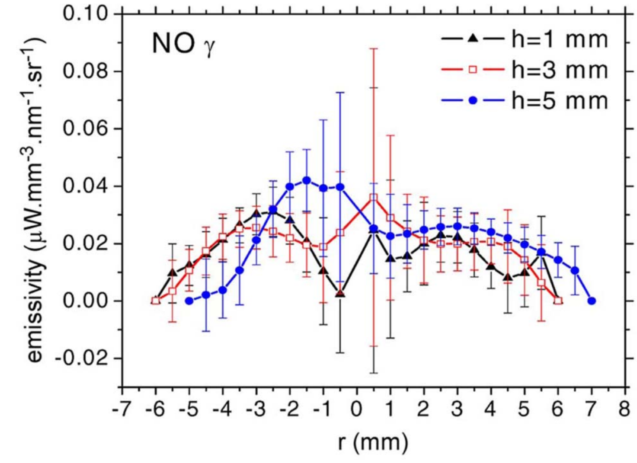

Fig. 3. Asymmetric Abel-inverted radial profiles of NO γ plasma emission in various heights ($P = 1.46$ kW, $Q = 15$ l/min).

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