2011-11-07

DC Pulsed Atmospheric Pressure Plasma Jet Image Information

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Recommended Citation

D.P. Dowling, et al., (2011) DC pulsed atmospheric pressure plasma jet image information. *IEEE Transitions on plasma science* 39/11-1, 2326-2327. DOI 10.1109/TPS.2011.2157978

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Abstract—**This paper presents optical imaging and optical emission spectroscopy (OES) data of an atmospheric-pressure plasma jet. It is shown how the visual information and OES information of the air discharge are related as the blown arc extends from the nozzle (2–4 mm) with a molecular nitrogen rotational temperature on the order of 1700 K and the flowing afterglow beyond this region is dominated by the cooler (300-K) NO–O chemiluminescent reaction that produces NO_2 species.**

Index Terms—**Atmospheric-pressure plasmas, optical emission, plasma applications, plasma temperature.**

ATMOSPHERIC plasma treatments are widely used to activate polymer surfaces prior to adhesive bonding. A key issue is to maximize the level of plasma activation (generally associated with the greatest reduction in water contact angle) while preventing thermal damage to the polymer substrate. The treatment studies were carried out using a commercial atmospheric-pressure air plasma system called PlasmaTreat. Among the atmospheric-pressure plasma jet (APPJ) activation studies reported to date with this source are those that aim to enhance the surface energy of polyethylene prior to adhesive bonding, adhesion improvement, and textile polymer treatments. To prevent thermal surface damage to polymers, the APPJ nozzle-to-surface distance is required to be in the range of 50–80 mm for static treatment; however, this gap distance can be reduced to 10–20 mm when the discharge is moved rapidly (10–80 m $\cdot$ min^{-1}) over the surface. In this study, visual information of an APPJ plume is correlated with optical emission spectroscopy (OES) measurement along the axial length of the discharge plume.

I. APPJ System

The APPJ OpenAir system uses dry compressed air as the working gas with an inlet pressure between 100 000 and 300 000 Pa and a flow rate between 37.5 and 76.6 L/min. The APPJ is driven by a unipolar square-wave pulsewidth modulation (PWM) power circuit switch. This circuit provides an immediate amount of electrical power between fully on and fully off at a drive switching frequency between 17 and 25 kHz [1].

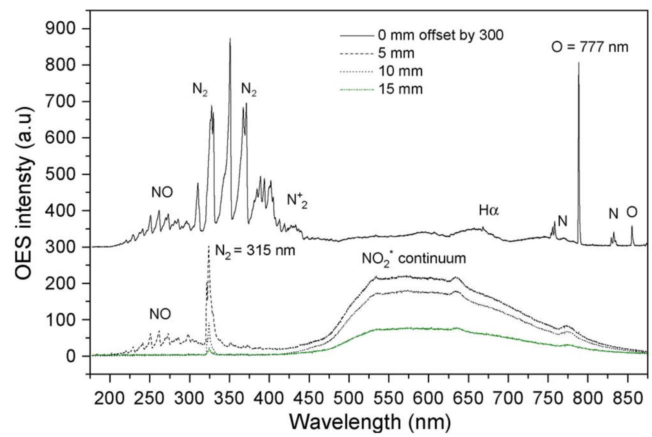

Fig. 1. Low-resolution OES (200–850 nm) of the discharge afterglow as a function of axial distance (0, 5, 10, and 15 mm). Drive frequency = 25 kHz, PCT = 100%, and air volume flow = 76.6 L/min.

II. OES Measurements

The spectrum by a low-resolution spectrometer for the OES survey as a function of fixed axial position (0, 5, 10, and 15 mm) within the discharge afterglow is shown in Fig. 1. Note that the 0-mm data are offset by +300 units for clarity. This figure shows two contrasting emission regions. The region close to the anode nozzle contains NOγ bands ($\lambda = 236-258$ nm), the second positive system of molecular N_2 ($C^3\Pi_u^+ - B^3\Pi_g^+$), and at $\lambda = 391$ nm, the $\nu = 0 \rightarrow 0$ band of the first positive nitrogen ions N_2^+ ($B^2\Sigma_u^+ - X^2\Sigma_g^+$) is observed. At longer wavelengths, the atomic-H-Balmer-α line at $\lambda = 656$ nm, nitrogen, and the O ($3p^5$P$-3s^5$S) at $\lambda = 777$ nm are also present. Moving away from the anode nozzle along the discharge axis, the optical emission undergoes an abrupt change in emission content at 5 mm, under the processing conditions used. Here, the excited NO_2 molecule ($\lambda = 450-800$ nm) continuum is formed with the second positive system of molecular N_2; atomic oxygen is greatly reduced, and the NOγ bands are still maintained. Continuing along the discharge axis line to 10 mm, the NO_2 continuum has decreased in intensity, and the NOγ bands are no longer present. At 15 mm, the NO_2 continuum intensity at 550 nm has decayed by one-half of that obtained at 5 mm.

Manuscript received November 30, 2010; revised April 25, 2011; accepted May 16, 2011. Date of publication June 23, 2011; date of current version November 9, 2011. This work was supported by SFI under Grant 08/SRC11411. V. Milosavljević is grateful to project No. 171006 of R. Serbia.

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Digital Object Identifier 10.1109/TPS.2011.2157978

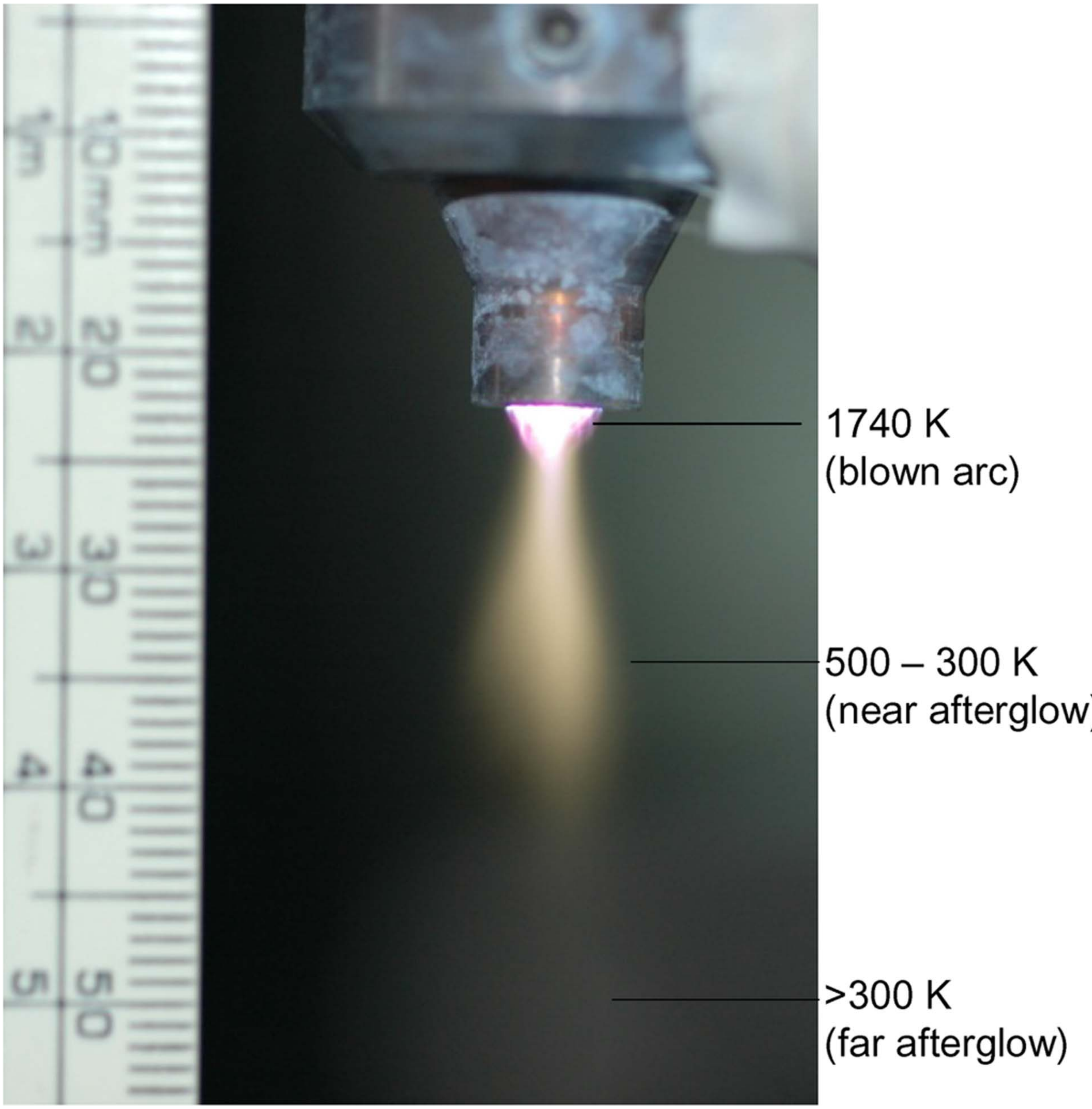

Fig. 2. Photograph of the APPJ illustrating the blown arc protruding from the nozzle. Conditions: PWM driving frequency = 19 kHz, PCT = 20%, 95% output voltage, and air volume flow = 37.6 L/min.

Using the procedure from [1] and [2], the rotational temperature is found to be in the range of 1709 ± 100 K at 25 kHz to 1761 ± 100 K at 19 kHz. These OES measurements demonstrate that, as the air is pushed through the arc region, nitrous oxide (NO) is formed, which then undergoes partial oxidation to the excited NO_2 state within the flowing afterglow. This process is represented by the NO–O chemiluminescent reaction

$$NO + O \rightarrow NO_2 + h\nu. \quad (1)$$

In conclusion, the air APPJ discharge was found to have two distinct plasma regions: the blown arc and the flowing afterglow region, where the flowing afterglow can be subdivided into near afterglow and far afterglow (see Fig. 2). Photodiode measurements reveal that the arc region has a time-modulated polychromic light emission that follows the PCT (effective duty cycle) of the applied power from the power supply.

ACKNOWLEDGMENT

The authors would like to thank K. Niemi for the simulation and measurement of the rotation temperature.

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