Images of Electrohydrodynamic Flow Velocity Field in a DC Positive Polarity Needle-to-Plate Nonthermal Plasma Reactor

J. Mizeraczyk, J. Dekowski, J. Podliński, M. Dors, M. Kocik, J. Mikielewicz, T. Ohkubo, and S. Kanazawa

***Abstract*—Images showing the flow pattern and velocity field in a positive polarity needle-to-plate nonthermal plasma reactor are reported. The images were obtained using the particle image velocimetry. They showed a strong secondary flow, caused by the electrohydrodynamic forces, which transport the working gas also in the upstream main-flow direction. This may influence operation of the nonthermal plasma reactors and affect their capability of gaseous pollutant remediation.**

***Index Terms*—Corona discharge, electrohydrodynamic flow, flow visualization, nonthermal plasma, particle image velocimetry.**

RECENTLY, nonthermal plasma techniques (e.g., [1], [2]) have become important for remediation of air polluted with various gaseous pollutants, such as acid gases (SO_x, NO_x, HCl etc.), greenhouse gases (CO_x, N_xO_y, para-fluorocarbons etc.), ozone depletion gases (freons, halons etc.), volatile organic compounds (VOCs, toluene, xylene etc.), and toxic gases (Hg, dioxins etc.). The main advantages of the nonthermal plasma techniques are low cost, high pollutant removal efficiency and small space volume.

Various aspects of the nonthermal plasma reactors have been widely studied [1], [2]. However, recently, a new phenomenon has been observed in a dc needle-to-plate nonthermal plasma reactor. Ohkubo *et al.* [3], measuring the two-dimensional distribution of ground-state NO density by laser induced fluorescence (LIF) in a needle-to-plate positive streamer corona during NO removing processing, observed that the concentration of NO molecules decreased not only in the discharge and downstream regions of the reactor, but also upstream of the discharge region. The reason for the decrease of the concentration of NO in the upstream region of the discharge is not clear at this moment. However, the results of the previous (e.g., [4]–[6]) and recent (e.g., [7]) experiments on the secondary flow (ionic wind) in electrostatic precipitators suggest that the electrohydrodynamic (EHD) flow is capable of transporting long-living active species (e.g., O_3) from the discharge region upstream, where they may oxidize NO molecules, causing their depletion, as observed experimentally by Ohkubo *et al.* [3].

The observation of Ohkubo *et al.* [3], showing the removal of NO in the upstream region, may have an important impact on the understanding of the physics and chemistry of the nonthermal plasma processing of gaseous pollutants and designing the nonthermal plasma reactors. This observation also showed that a better understanding of the nonthermal plasma processing requires including the gas flow, which have been neglected.

In this paper, we present results of particle image velocimetry (PIV) measurements of the velocity field in a positive-polarity needle-to-plate nonthermal plasma reactor. The reactor is comprised of a conventional needle electrode made of a brass rod (6 mm in diameter), the end of which had a tapered profile with the tip having a radius of curvature of 0.5 mm. The grounded electrode was a stainless-steel plate. The interelectrode distance was 5 cm. The average velocity of the main gas flow (air) was 0.05 m/s. The standard deviation of the mean flow velocity was $\pm$4%. The operating voltage was up to 33 kV.

The monitoring of the flow pattern and measurement of the velocity field were carried out with standard PIV equipment (Dantec PIV 1100) consisting of a twin second harmonic Nd–YAG laser system ($\lambda = 0.53$ μm, pulse energy 50 mJ) and an image processor (Dantec PIV 1100). The laser "sheet" of thickness 1 mm was parallel to the flow direction and perpendicular to the plate electrode. The area of the measured velocity field was 5 cm $\times$ 11 cm. The images of the seeding particles (smoke following the flow) in the laser "sheet" were recorded by a Kodak Mega Plus ES 1.0 charge coupled device (CCD) camera that enabled capturing two images with a time separation of 2 μs. The CCD camera active element size was 1008 $\times$ 1018 pixels.

Typical images of the flow pattern and velocity field in the upstream region of the reactor are shown in Fig. 1(a) (single image) and (b) (averaged over 30 single laser shots). Due to the laser beam shadow behind the positive electrode rod, in this experiment we were able to record reliable images only in the space below the rod. Therefore, the results show only the part of the flow pattern in the reactor. Experiments on measuring the flow pattern in the entire reactor are under preparation.

The results show a strong secondary flow in the upstream region of the reactor. The velocity of the secondary flow was up to 2.5 m/s in the discharge area, and about 0.6 m/s near the plate and up to 10 cm from the needle electrode in the upstream direction. The secondary flow was highly turbulent, the deviation of the secondary-flow velocity was about $\pm$30%.

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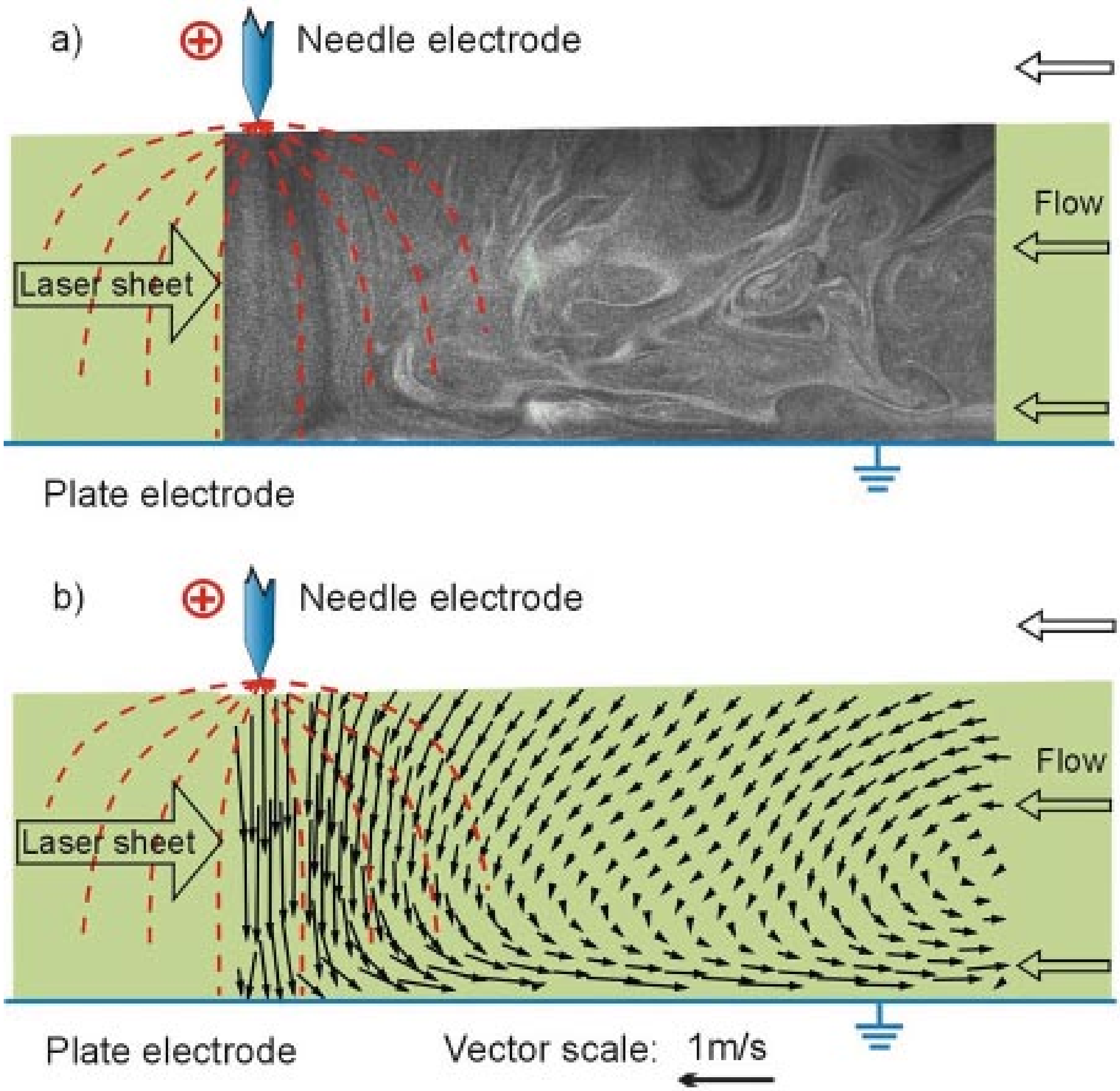

Fig. 1. (a) Flow pattern and (b) velocity field in dc positive polarity needle-to-plate nonthermal plasma reactor. Operating voltage $U = 22.1$ kV, mean main-flow velocity $V = 0.05$ m/s, electrohydrodynamic number $N_{EHD} = 100$. The length of the vectors in (b) is proportional to the velocity. The dashed lines illustrate the streamer corona discharge area.

These results show that there exists a strong secondary flow in the nonthermal plasma reactor. This fact has to be taken into account when the modeling of the nonthermal plasma processes (e.g., [8]) and the designing of the reactors are considered. We believe that the obtained results will be also helpful for elucidating the phenomenon observed by Ohkubo *et al.* [3].

REFERENCES

[1] B. M. Penetrante, J. N. Bardsley, and M. C. Hsiao, "Kinetic analysis of nonthermal plasmas used for pollution control," *Jpn. J. Appl. Phys.*, vol. 36, pp. 5007–5017, 1997.

[2] K. Urashima and J. S. Chang, "Removal of volatile organic compounds from air streams and industrial flue gases by nonthermal plasma technology," *IEEE Trans. Dielect. Elect. Insulation*, vol. 7, pp. 602–614, Oct. 2000.

[3] T. Ohkubo, S. Kanazawa, Y. Nomoto, and J. Mizeraczyk, "Two-dimensional distribution of NO by LIF technique in a corona radical shower reactor during NO_x removal processing," in *35th Annu. Meeting—IEEE Industry Applications Society*, vol. 1–2, Roma, Italy, 2000, pp. 864–867.

[4] L. B. Loeb, *Electrical Coronas*. Berkeley, CA: Univ. of California Press, 1965, pp. 402–407.

[5] T. Yamamoto and H. R. Velkoff, "Electrohydrodynamics in an electrostatic precipitator," *J. Fluid Mech.*, vol. 108, pp. 1–18, 1981.

[6] P. Atten, F. M. J. Mccluskey, and A. C. Lahjomri, "The electrohydrodynamic origin of turbulence in electrostatic precipitators," *IEEE Trans. Ind. Applicat.*, vol. 23, pp. 705–711, July/Aug. 1987.

[7] J. Mizeraczyk, M. Kocik, J. Dekowski, M. Dors, J. Podliński, T. Ohkubo, S. Kanazawa, and T. Kawasaki, "Measurements of the velocity field of the flue gas flow in an electrostatic precipitator model using PIV method," *J. Electrostatics*, vol. 51–52, pp. 272–277, 2001.

[8] A. C. Gentile and M. J. Kushner, "Reaction chemistry and optimization of plasma remediation of N_xO_y from gas streams," *J. Appl. Phys.*, vol. 78, pp. 2074–2085, 1995.