Flow velocity field in flow stabilized hollow needle–to–plate electrical discharge in atmospheric pressure air

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The objective of this work was to study the flow velocity field in a reactor with a hollow needle–to–plate discharge stabilized by the air flow from the needle(s). The Particle Image Velocimetry (PIV) measurements showed that after reaching the plane electrode the fast air flow from the needle (average velocity of 200 m/s) spreads and flows with a velocity of up to 100 m/s in a narrow layer (up to 1 mm thick) along the plane electrode outwards. The bulk air mass in the reactor is not stagnant but circulates with a velocity of 1–5 m/s. The relatively fast air flow along the flat electrode is caused by the massive air outcome from the hollow needle(s) rather than by the electrohydrodynamic (EHD) effect, which is typical of the non–thermal plasma reactors without flow stabilization of the discharge.

1   Introduction

Several types of the non–thermal plasma reactors with various kinds of the electrical discharges (dielectric barrier discharge, DC and pulsed corona discharge, DC atmospheric pressure discharge stabilized by a fast gas flow) have been proposed for the abatement of gaseous pollutants (e.g. [1, 2]). Recently, a new version of the DC atmospheric pressure discharge, a so–called atmospheric pressure hollow needle–to–plate (HN–to–P) electrical discharge has been proposed [3, 4] for gaseous pollutant destruction. In the HN–to–P reactor the discharge is stabilized similarly as in the atmospheric pressure flow stabilized corona [5] and corona radical shower discharge [6], i.e. by a gas flow through the hollow needle(s). However, in the HN–to–P discharge the gas flow velocity through the needle (about 150 m/s) and averaged discharge current (about 1 mA per needle) are higher than those in [5] and [6], while the interelectrode gap (several millimetres) is shorter.

The HN–to–P discharge was tested in the decomposition of hydrocarbons (HC), proving its potential for gaseous pollutant abatement [4]. The test showed that the HC decomposition efficiency strongly depends on the residence time of the operating gas in the reactor. However, the residence time is dependent on many factors associated with a complicated gas flow pattern in the HN–to–P discharge reactor, resulted from the gas expansion from narrow needle(s), back reflection of the gas stream from the counterelectrode, mixing of the flows if many needles are used, etc.

To elucidate the flow effects in the HN–to–P discharge we measured the flow velocity fields in a reactor with one or three hollow needles, using Particle Image Velocimetry (PIV) method. The results are presented in this paper.

2   Experimental set–up

The experimental set–up, consisted of a reactor, power and gas supply units, and PIV measuring system is shown in Fig. 1. The reactor, similar to that presented in [3] and [4], was a rectangular acrylic box of a height of 10 cm or 2 cm, width – 20 cm and length – 50 cm. In the middle of the reactor one or three stainless steel hollow needles (of an outer diameter of 1.8 mm and inner diameter of 1.2 mm) were placed as the stressed electrode(s). The tip of each hollow needle was sharpened at an angle of 15°, forming an elliptic outlet. The needles were placed perpendicularly to a stainless steel plate, which was used as the grounded electrode. The distance between each hollow needle tip and the plate was 3.9 mm. When 3 needles were used the distance between them was 8 mm and the elliptic outlets of all needles were oriented in the same direction. The experiment was carried out with dry air which flowed through the needles with a flow rate of 13 l/min per needle. No other forced flow was applied.
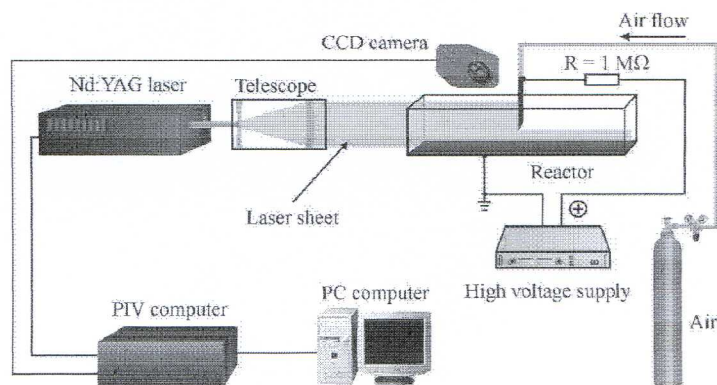

Fig. 1. Experimental set–up.

Each hollow needle was supplied separately from a dc source through a resistor of 1 MΩ resistanceu The needles were polarised positively. The time–averaged discharge current was 1 mA per needle at the applied voltage of about 7 kV.

PIV method is based on observation of the laser light scattered by the seeding particles following the flow. In this experiment cigarette smoke was used as seeding. It was added either to the air flowing through the hollow needle(s) or to the air present in the reactor. The PIV measurements of the flow velocity field in the reactor were carried out with a 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) – Fig. 1. The laser "sheet" of a thickness of 1 mm was formed from the Nd–YAG laser beam by a telescope and set along the reactor through the needle electrode, parallel to the side walls. The observation area was either that situated to the left of the single needle electrode (or of the first from the three electrodes) or below the electrode(s) – see Fig. 1. The images of the particles following the flow in the laser "sheet" were recorded by a Kodak Mega Plus ES 1.0 CCD camera that enabled us capturing two images with the minimum time separation of 2 μs. The captured images were transmitted by the image processor to a PC computer. Then, a flow velocity map was calculated from the acquired images.

The flow velocity field presented in this paper were obtained after averaging 30 individual flow velocity maps captured in $2 - 40$ μs depending on the measurement area. We estimate that the error in the velocity measurement was ± 5 %.

3   Results

Generally, we found that the electrical discharge did not influence the velocity field pattern in the reactor. This concerns the region just below the hollow needle(s), where the air velocity is very high (about 200 m/s) as well as the other regions (the bulk air) where velocities are in the range of 1–5 m/s. Thus, Figs. 2–6 show the velocity field patterns in the reactor for both cases, with and without the discharge.

No difference in the flow pattern in the HN–to–P reactor with or without discharge suggests that the flow structures are determined by the massive air outcome from the hollow needle(s) rather than by the electrohydrodynamic (EHD) effect, which may play an important role in the non–thermal plasma reactors without flow stabilization of the discharge [7].

3.1   Single hollow needle electrode

Fig. 2 shows the velocity field pattern in the single hollow needle electrode reactor of 10 cm high. As it can be seen from the velocity field blow–up, after reaching the plane electrode the fast air flow from the needle (about 200 m/s) spreads and flows (with a velocity up to 100 m/s) in the narrow layer (less than 1 mm thick) along the plane electrode outwards. The relatively fast air flows from the needle along the plane electrode forces the bulk air flow in the entire measurement area, more or less perpendicularly to the plane electrode. The bulk air moves towards the plane electrode in a turbulent way with the standard deviation of flow velocity of about ± 50 %.

When the reactor was 2 cm high the air flow below the hollow needle was similar to that in the 10 cm high reactor (see the blow–up in Fig. 2). However, the velocity field pattern in the bulk air volume is different (Fig. 3). In the 2 cm high reactor, a regular vortex, not present in the 10 cm high reactor, is formed close to the plate, about 3 cm from the needle. The bulk air circulates in the whole measurement area towards the needle outlet. It gives impression of sucking the air present in
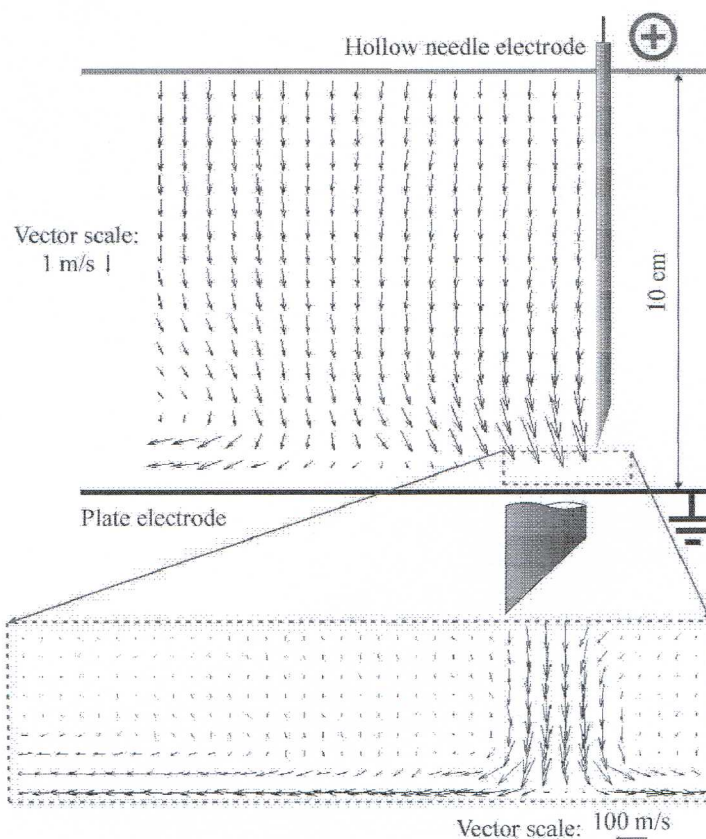
Fig. 2. Velocity field in the HN–to–P discharge reactor with single hollow needle. The height of the reactor was 10 cm. Area of the measurement − 10 cm × 10 cm, and 18 mm × 3.9 mm (blow–up). The length of velocity vector is proportional to its velocity (see the vector scale).

the reactor by the fast flow from the needle. However, it must be noticed that the measurements of the velocity field were carried out only in one plane, passing through the needle, parallel to the reactor side walls. To know the comprehensive flow velocity field pattern in the reactor, three dimensional map of the velocity field has to be measured.

3.2 Three hollow needle electrodes

The flow velocity field pattern in the measurement area on the left from the first electrode in the 10 cm high reactor with 3 needle electrodes (Fig. 4) is similar
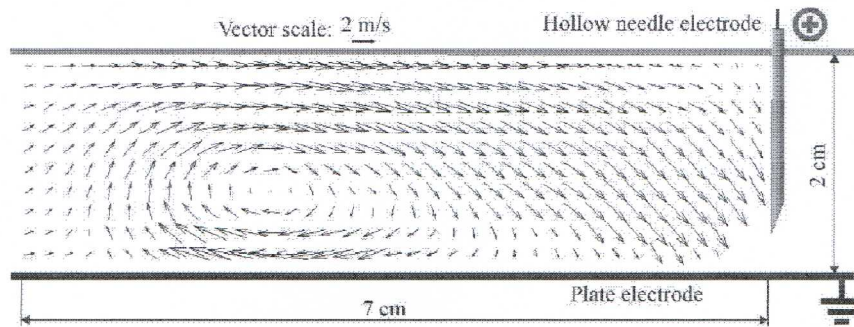
Fig. 3. Velocity field in the HN–to–P discharge reactor with three hollow needles. The height of the reactor was 10 cm. Area of the measurement – 10 cm × 10 cm.

to that in the single needle electrode reactor (Fig. 2). However, the air flow in the vicinity of the plate electrode is faster in the three needle electrode reactor (3.8 m/s compared to 1.6 m/s in the single needle electrode reactor). This is due to the higher total air mass outcome from 3 needle electrodes (39 l/min).
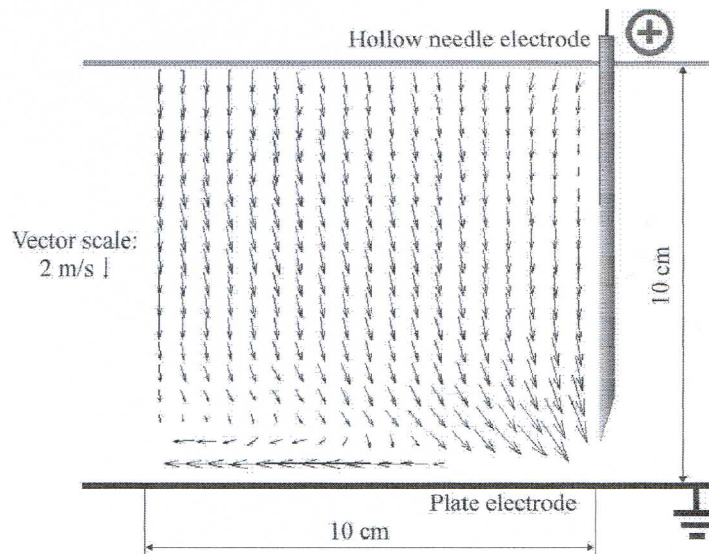

Fig. 4. Velocity field in the HN–to–P discharge reactor with three hollow needles. The height of the reactor was 10 cm. Area of the measurement – 10 cm × 10 cm.

In the 10 cm high reactor, the air flow in the area below the electrodes forms 2 regular turbulent structures, a structure with two opposite directed vortexes between one pair of the electrodes, and a structure with one vortex between the other electrode pair (Fig. 5). It seems that both structures belong to the stable modes of the velocity field pattern, which can exist in the present flow–electrode arrangement.
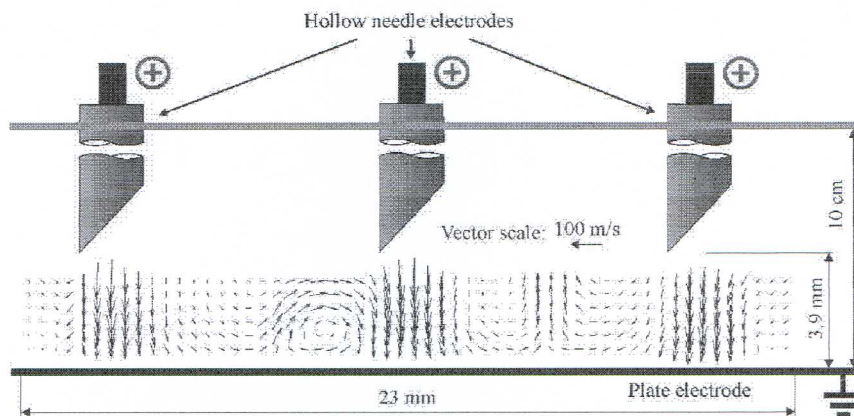

Fig. 5. Velocity field in the HN–to–P discharge reactor with three hollow needles. The height of the reactor was 10 cm. Area of the measurement − 23 mm × 3.9 mm.

In the 2 cm high reactor, a regular vortex is formed in the measurement area on the left from the first electrode (Fig. 6), like in the single needle electrode reactor (Fig. 3). However, the vortex in the three needle electrode reactor is smaller and placed closer to the needle electrode.

The flow structure below the needles in the 2 cm high reactor is similar to that in the 10 cm high reactor (Fig. 5).

4 Conclusions

The results of the velocity field measurements in the HN–to–P discharge reactor with one or three hollow needles showed that the air flowing out of the hollow needle(s) with very high velocity (up to 200 m/s) spreads out and flows in the thin layer close to the plate electrode with a velocity up to 100 m/s. This relatively fast flow in the near electrode layer initiates formation of the turbulent flow of the bulk air in the reactor. The flow pattern of the bulk air exhibits regular vortex structures, if the reactor is 2 cm high. The electrical discharge practically does not influence flows of the air in the reactor due to the high velocity of the air from the hollow needle(s). This means that the role of the EHD flow in forming the flow pattern in the HN–to–P reactor is negligible, contrary to the non–thermal plasma
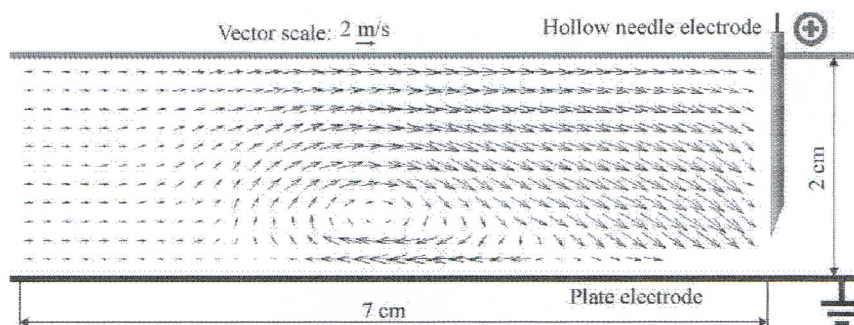
Fig. 6. Velocity field in the HN–to–P discharge reactor with three hollow needles. The height of the reactor was 2 cm. Area of the measurement – 7 cm × 2 cm.

reactors without flow stabilization of the discharge.

The presented experimental results show that the strong transport of the operating gas, including gaseous species (e.g. ozone) produced in the discharge [8, 9] has to be considered when modeling the plasma chemistry processes in the HN–to–P reactors.

### References

[1] J. S. Chang: in *Non–thermal Plasma Techniques for Pollution Control*, Eds. B.M. Penetrante and S.E. Schultheis, Springer–Verlag Berlin Heidelberg, NATO ASI Series, G 34 (A), 1–32, 1993

[2] E. M. Van Veldhuizen: in *Electrical Discharges for Environmental Purposes*, Nova Science Publishers, New York, 2000

[3] S. Pekarek, V. Kriha, M. Simek, R. Balek, F. Hanitz: Plasma Sources Sci. Technol. **8** (1999) 513–518

[4] S. Pekarek, V. Kriha, M. Pospisil, I. Viden: J. Phys. D: Appl. Phys. **34** (2001) L117–L121

[5] I. Maezano, J. S. Chang: J. Appl. Phys. **64** (1988) 3322–3324

[6] T. Ohkubo, S. Kanazawa, Y. Nomoto, J. S. Chang, T. Adachi: IEEE Trans. Ind. Appl. **30** (1994) 856–860

[7] J. Mizeraczyk, J. Dekowski, J. Podliński, M. Dors, M. Kocik, J. Mikielewicz, T. Ohkubo, S. Kanazawa: IEEE Trans. on Plasma Science **30** (2002)

[8] S. Pekarek, J. Rosenkrantz, V. Kriha: Czech. J. Phys. **50** (2000) 385–388

[9] S. Pekarek, J. Rosenkrantz: Ozone Science and Engineering (2002) in print
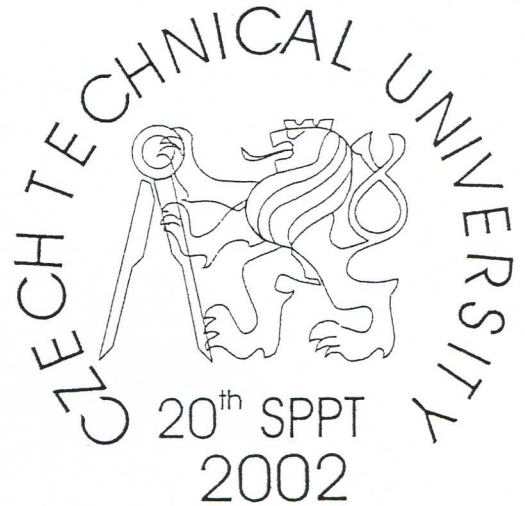
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PROGRAMME & ABSTRACTS

Velocity Field in Flow Stabilized Hollow Needle-to-Plate Electrical Discharge in Atmospheric Pressure Air

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For abatement of gaseous pollutants several types of the non-thermal plasma reactors have been proposed [1]. In these reactors various kinds of the electrical discharges are used. Recently, a new version of the DC atmospheric pressure discharge, so-called atmospheric pressure hollow needle-to-plate discharge (HNPD), was proposed in [2]. In this case the discharge is stabilized by a gas flow through the needle(s). This HNPD was tested for the decomposition of hydrocarbons (HC) [3]. It was shown that the HC decomposition efficiency strongly depends on the residence time of the operating gas in the reactor. The residence time, however, depends on many factors, which are associated with a complicated gas flow pattern in the HNPD reactor (gas expansion from narrow needle(s), back reflection of the gas stream from the counter-electrode, mixing of the flows if many needles are used, etc.).

In this paper we present the results of studies of the gas flow velocity field in a single HNPD stabilized by air flow through the needle. The electrode arrangement and discharge parameters are similar to those presented in [3]. The stainless steel needle electrode is situated perpendicularly to the stainless steel plane electrode. The air into the discharge volume is supplied through the needle. The velocity field at the flow around the needle is measured by PIV method [4]. The PIV measurements show that after reaching the plane electrode the strong airflow from the needle spreads and flows in the narrow layer along the plane electrode outwards. This relatively fast airflow (several m/s) along the plane electrode forces a flow in the entire reactor volume, more or less perpendicularly to the plane electrode. The bulk air volume is not stagnant but moves towards the plane electrode. The fast airflow along the flat electrode is caused by the massive air outcome from the needle rather than by the EHD effect, typical for non-thermal plasma reactors [4].

[1] E.M. van Veldhuizen, Electrical Discharges for Environmental Purposes, Nova Science Publishers, Inc., New York, 1999

[2] S. Pekarek, V. Kriha, M. Simek, R. Balek, Plasma Sources Sci. Technol., 8, 513-518, 1999

[3] S. Pekarek, V. Kriha, M. Pospisil, I. Viden, J. Phys. D: Appl. Phys., 34, L117-L121, 2001

[4] J. Mizeraczyk, J. Dekowski, J. Podliński, M. Dors, M. Kocik, J. Mikielewicz, T. Ohkubo, S. Kanazawa, 3rd Triennial Special Issue "Images in Plasma Science" of the IEEE Trans. Plas. Sci., 2002 (in print)