3D PIV measurements of the EHD flow patterns in a narrow electrostatic precipitator with wire–plate or wire–flocking electrodes

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The results of 3–dimensional (3D) Particle Image Velocimetry (PIV) measurements of the electrohydrodynamic (EHD) flow patterns in a narrow electrostatic precipitator (ESP) are presented in this paper. The ESP was an acrylic parallelepiped with a wire discharge electrode and two plane collecting electrodes. In contrary to typical ESPs the wire electrode was placed along the gas flow, in the ESP centre, in the halfway between collecting electrodes. Either two smooth stainless steel plates or two stainless steel meshes with nylon flocks were used as the collecting electrodes. They were placed on the top and bottom of the ESP. The PIV measurements were carried out in two parallel planes, placed perpendicularly to the collecting electrodes and parallel to the wire electrode. The obtained results showed some similarities and differences of a 3D particle flow in the ESP with plate or flocking electrodes.

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1 Introduction

The rapid development of laser technique in the past decade allows introducing new measuring methods into various areas of scientific and technical activities. One of such methods is Particle Image Velocimetry (PIV) [1]. The PIV method based on the scattering of laser light on the particles following the flow has been introduced to measure the flow velocity fields in large cross–sections of the flow. This method gives a unique possibility to measure the velocity field in the flow with a high electrical field, where classical hot–wire thermo–anemometry can not be used. The 2–dimensional (2D) PIV has already been employed for studying flow patterns in electrostatic precipitators [2–6]. Recently we introduced 3–dimensional (3D) PIV technique for studying the flow in electrostatic precipitators (ESPs).

In this paper our results of 3D PIV measurements of electrohydrodynamic (EHD) flow velocity fields in a narrow ESP with wire–plate or wire–flocking electrodes are presented.

2 Experimental apparatus

The apparatus used in this experiment consisted of an ESP, high voltage supply and standard PIV equipment for the measurement of velocity fields (Fig. 1).

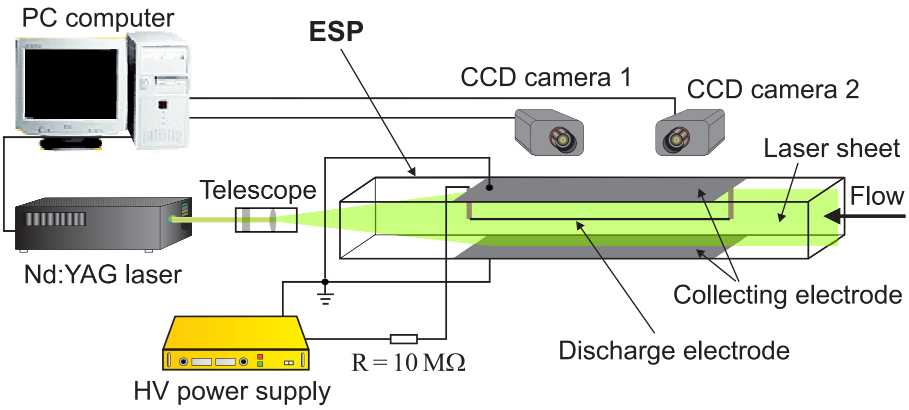

Fig. 1. Experimental set–up.

The ESP was a narrow acrylic parallelepiped 90 mm long, 30 mm wide and 30 mm high. The electrical electrode set consisted of a stainless steel wire discharge electrode and two plane collecting electrodes. The wire electrode was 60 mm long and 0.1 mm in diameter. In contrary to typical ESPs the wire electrode was placed along the gas flow, in the ESP centre, in the halfway between collecting electrodes. The collecting electrodes, 60 mm long and 30 mm wide, were placed on the top and bottom of the ESP. Either two smooth stainless steel plates or two stainless steel meshes with nylon flocks were used as the collecting electrodes. A flow homogenizer was placed before the ESP inlet.

The negative or positive DC voltage of up to 9.5 kV was applied to the wire electrode through a 10 MΩ resistor, while the collecting electrodes were grounded. Air flow seeded with dry cigarette smoke was blown along the ESP duct with an average velocity of 0.5 m/s. The PIV measurements were carried out in two parallel planes, placed perpendicularly to the collecting electrodes and parallel to the wire electrode (Fig. 2). Due to the limited size of this paper only selected results are presented.

The 3D PIV equipment was based on two CCD cameras connected to the PIV computer. These cameras were focused on the observation area at different angles, as shown on Fig. 1. It enabled us (after calibration process) to get all three components of the velocity in measured planes.

All the velocity fields presented in this paper resulted from the averaging of

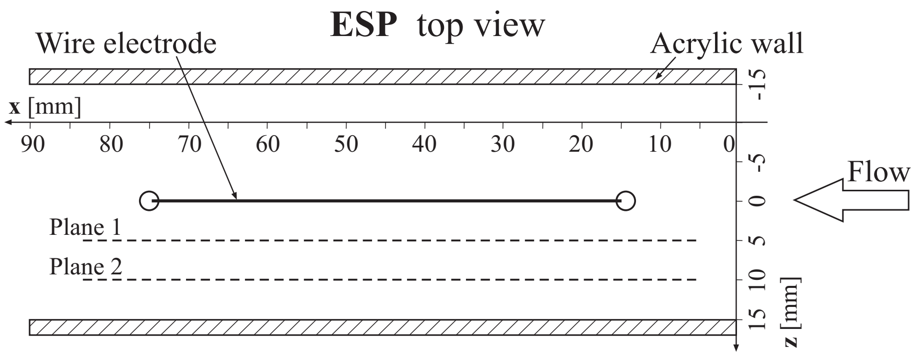

Fig. 2. Top view of the ESP. The measurement planes are marked.

100 measurements, which means that each velocity map was time–averaged. Based on the measured velocity fields (velocity x– and y–components), the apparent flow streamlines of a hypothetical 2–D flow were calculated.

3 Results

Figs. 3–6 show the flow velocity fields measured in the ESP at a flow average velocity of 0.5 m/s. At this velocity the Reynolds number was $Re = VL/\nu = 955$ (the parameters used to calculate Re were: the primary flow velocity $V = 0.5$ m/s, characteristic length (plate–plate distance) $L = 0.03$ m, and air dynamic viscosity $\nu = 1.57 \times 10^{-5}$ m^2/s).

The flow velocity field in the plane 1 in the wire–plate ESP without voltage is showed in Fig. 3. As can be seen, the flow is uniform in the whole measured area. Very similar results were obtained in the plane 2 in this ESP and in the planes 1 and 2 in the wire–flocking ESP. When no voltage was applied the flow in the ESP was laminar.

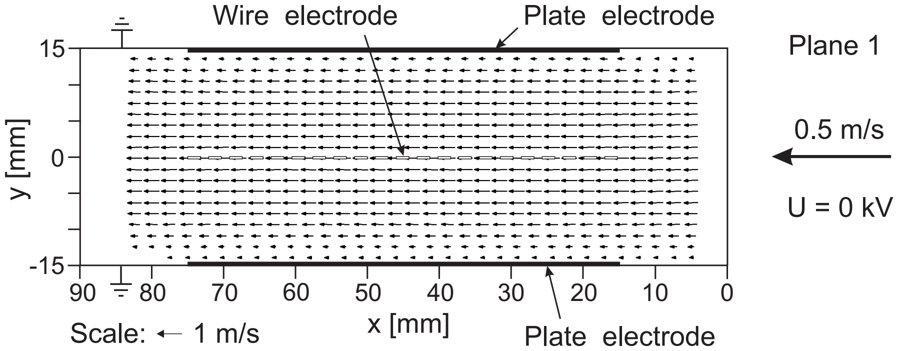

Fig. 3. Flow velocity field (x– and y–components) in the plane 1 when no voltage was applied.

When the high voltage is applied, the EHD force (equal to ρE per volume unit, where ρ is the ion density, E is the electric field) moves the ions causing strong secondary flow which alters significantly the original, primary flow. Results of our measurements show, that three–dimensional flow is generated in the ESP.

Figs. 4 and 5 show the 3D flow velocity fields in the wire–plate ESP for negative voltage of 7.7 kV. The total discharge current was 30 μA. The 3D flow velocity field in the wire–plate ESP in the plane 1 placed 5 mm from the wire electrode is shown in Fig. 4. As can be seen, the gas flow is directed along the ESP duct and in the discharge region from the ESP centre to the plate electrodes. The flow pattern observed for velocity z–component is quite clear too. In the central part of the ESP duct, along the discharge region, the gas flows in the direction of the wire electrode, and near the plate electrodes the gas flows in the opposite direction, i.e. in the side wall direction. The velocity z–component reaches values from -0.3 m/s to 0.25 m/s.

Fig. 5 shows the 3D flow velocity field measured in the wire–plate ESP in the plane 2, placed 10 mm from the wire electrode i.e. 5 mm from the side wall. In this plane, in the first $10 \div 15$ mm of the discharge region, the gas flows in the direction of the plate electrodes, then in the next $10 \div 15$ mm the gas flows along the plates and finally from the plate electrodes to the ESP centre. The flow pattern for velocity z–component is very similar as in the plane 1, but with higher velocities.

From the measurements presented in Figs. 4 and 5 one can deduce, that in the ESP with a wire electrode placed longitudinally–to–flow the gas flows along the ESP duct and whirls. The pair of spiral vortices occurs. The gas flows from the ESP centre (near the discharge wire electrode) to the plate electrodes, afterwards near the plate electrodes to the side wall, then near the side wall to the ESP centre and finally to the wire electrode.

The *EHD* number $[EHD = IL^3/(\nu^2 \rho \mu_i A)]$ [7], based on the flow channel data, was 3×10^6. Hence, the ratio of the *EHD* number to the Reynolds number squared (EHD/Re^2) was 3.3. The parameters used to calculate *EHD* were: the total discharge current $I = 30$ μA, characteristic length (plate–plate distance) $L = 0.03$ m, air dynamic viscosity $\nu = 1.57 \times 10^{-5}$ m^2/s, air density $\rho = 1.205$ kg/m^3, ion mobility $\mu_i = 2.55 \times 10^{-4}$ m^2/Vs, and discharge area (60 mm long and 30 mm wide discharge area on the two plate electrodes) $A = 0.0036$ m^2. The uniform current distribution on the plate electrodes was assumed.

Fig. 6 shows the 3D flow velocity field in the wire–flocking ESP for negative voltage of 7.6 kV. The total discharge current was 42 μA. The flow patterns measured in the wire–flocking ESP (plane 2 presented in Fig. 6) are similar to those occurred in the wire–plate ESP. The main difference is that the flow velocities are much lower, especially near the flocking electrodes. This is considered as an advantage because the lower flow velocity near the collecting electrodes prevents the re–entrainment of the particles deposited on the collecting electrodes. The EHD number was 4.2×10^6 and the ratio of the EHD number to the Reynolds number squared was 4.6.

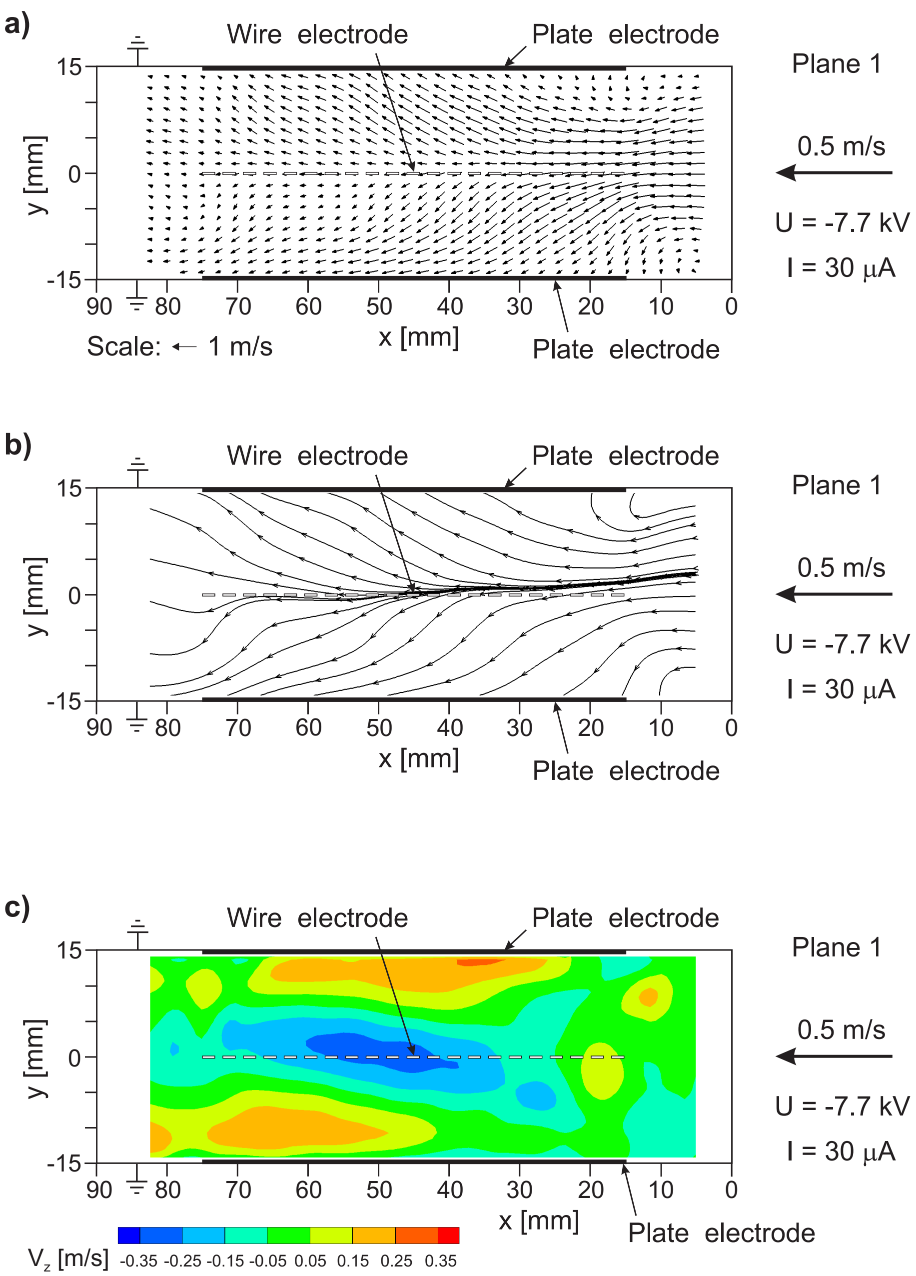

Fig. 4. The results of 3D measurement in the plane 1 in the wire–plate ESP. Flow velocity field in the $x - y$ plane (a), corresponding flow streamlines (b), and flow velocity z–component (c).

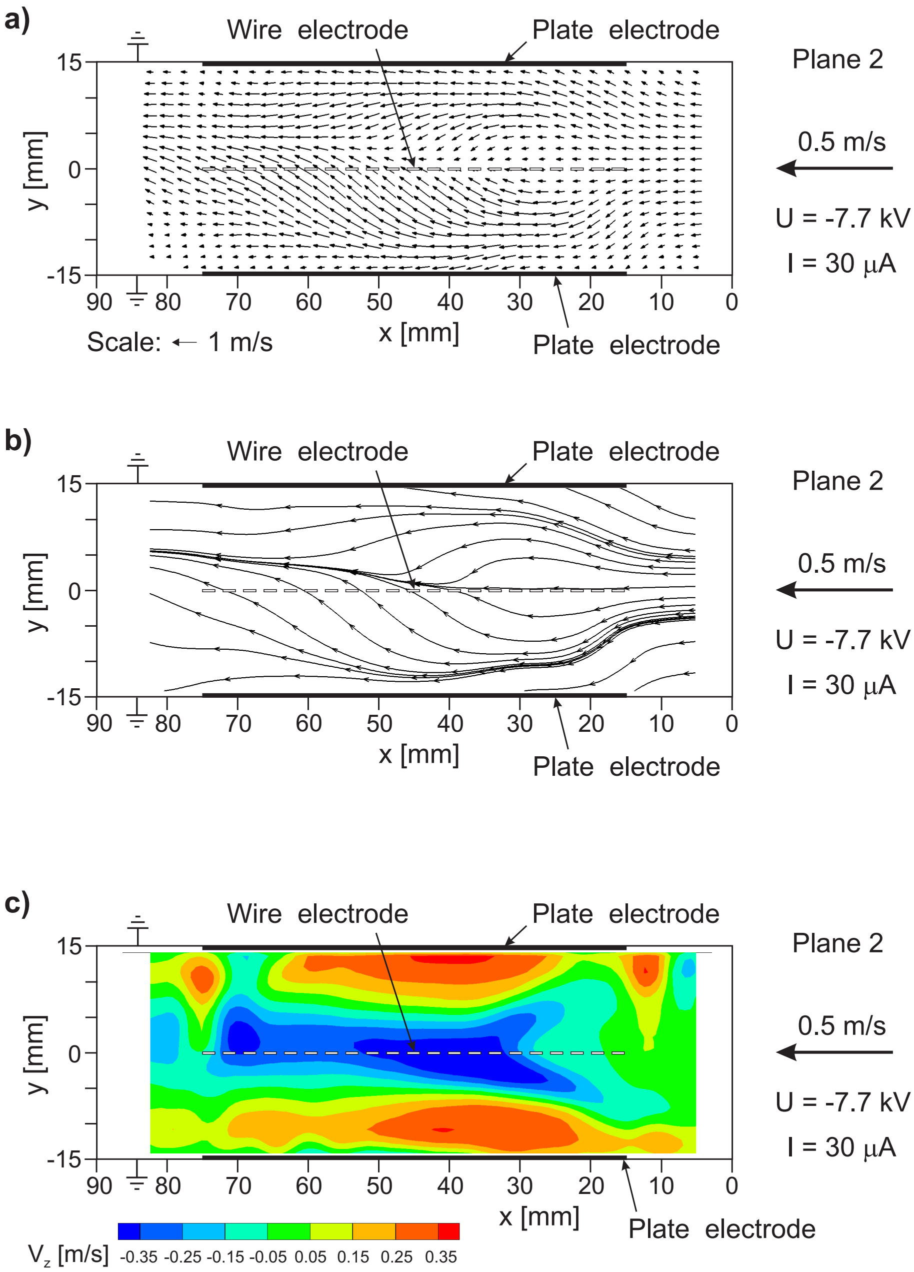

Fig. 5. The results of 3D measurement in the plane 2 in the wire–plate ESP. Flow velocity field in the $x-y$ plane (a), corresponding flow streamlines (b), and flow velocity z–component (c).

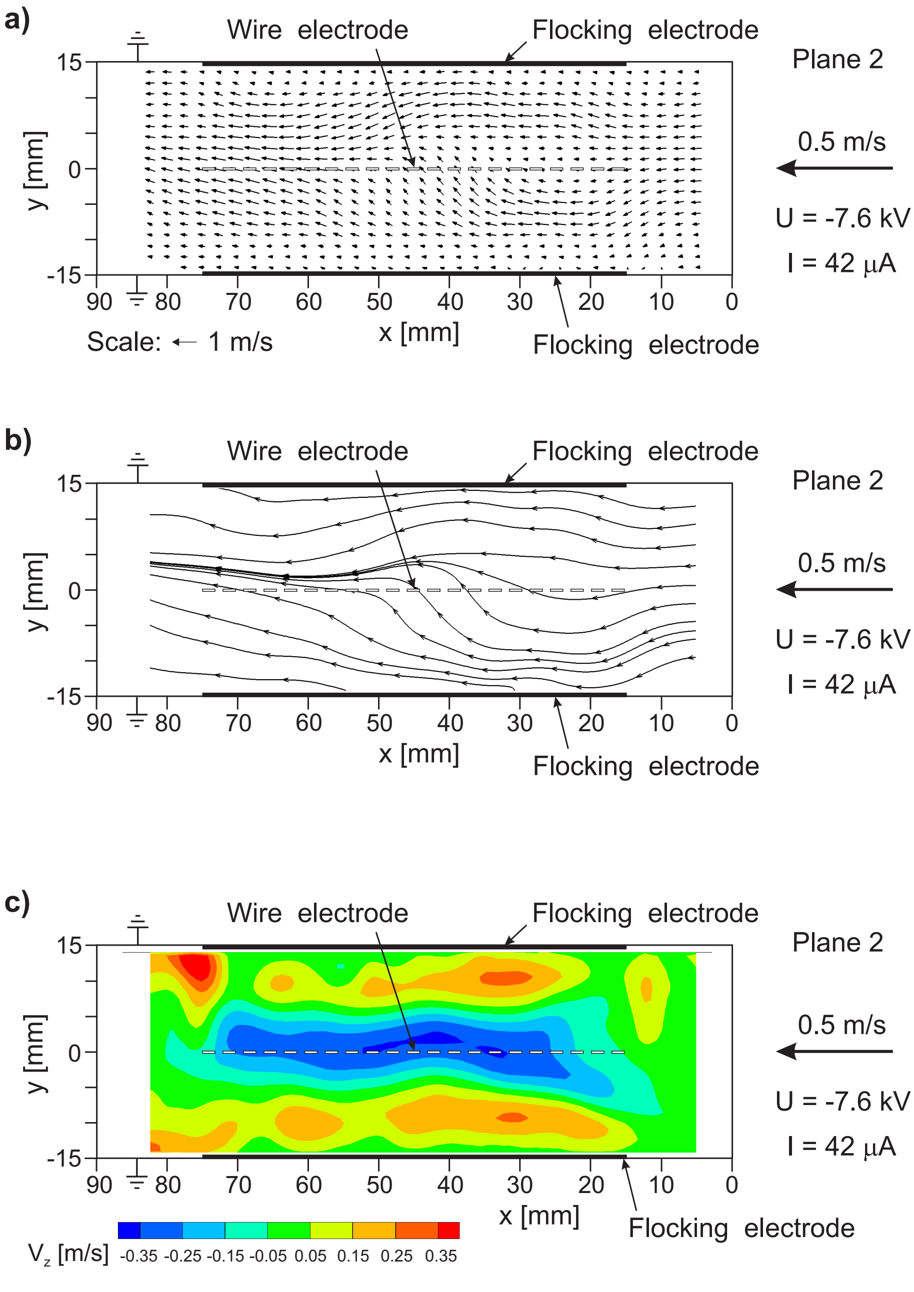

Fig. 6. The results of 3D measurement in the plane 2 in the wire–flocking ESP. Flow velocity field in the $x - y$ plane (a), corresponding flow streamlines (b), and flow velocity z–component (c).

4 Summary and conclusion

In this paper results of the 3D PIV measurements of the flow velocity fields in the narrow ESP with wire–plate or wire–flocking electrodes are presented. The wire electrode was placed along the gas flow, in the ESP centre. The measurements were carried out in two parallel planes, fixed perpendicularly to the plate electrodes, along to the direction of the primary flow.

The results show that the EHD secondary flow interacts strongly with the primary flow. In the ESP with a wire electrode placed longitudinally–to–flow the spiral vortices occurs. These spiral vortices spread out along the ESP and do not block the primary flow, as it was observed for ESPs with wire electrode placed perpendicularly to the primary flow [2–6]. It suggest, that in the ESPs with the wire electrode placed longitudinally–to–flow the pressure drop should be smaller.

Our measurements show that the flow patterns for the smooth–plate electrodes and for the flocking electrodes are similar in the bulk of the flow. However, the flow velocities near the flocking electrodes are much lower than near the smooth electrodes. This is considered as an advantage because the lower flow velocity near the collecting electrodes prevents the re–entrainment of the particles deposited on the collecting electrodes.

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