Flow Distribution Measurement in Wire-nonparallel Plate Type Electrohydrodynamic Gas Pump by a Particle Image Velocimetry

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ABSTRACT

2D Particle Image Velocimetry (PIV) measurements were performed in a wire-nonparallel plates type electrohydrodynamic (EHD) gas pump. The effect of electrode configuration and polarity of the active electrode on the flow pattern inside the pump was studied. One can deduce from the obtained flow patterns that the flow generated inside the EHD pump is three dimensional. The vortices formed inside the EHD gas pump have negative effect on pumping capabilities of the pump since the vortices may block and suppress the generated flow. The PIV results will be compared with a numerical modelling of the flow, based on k-E model.

Index Terms — Particle image velocimetry, PIV, electrohydrodynamic pump, EHD, corona discharges, non-thermal plasmas.

1 INTRODUCTION

WHEN a high electric field is applied between high voltage and grounded electrodes in a gas medium, a corona discharge is formed by an ionization of the gas molecules. Thus ion flux along the electric field transfers its momentum to the weakly dipole neutral molecules. This results in the so-called ionic wind or an electrohydrodynamically induced gas flow [1-10]. When the electrode configuration forms an unsymmetrical electric field distribution, the unidirectional gas flow can be generated, i.e. the EHD gas pumping [5]. Several electrode geometries have been studied for EHD gas pumps, such as needle-to-mesh, needle-to-ring, wire-to-rod, wire-nonparallel plates etc. [1-10], however, sharp edge electrode such as needle ore blade usually become unstable due to transition from corona to spark discharge [5].

In this work, the potential three-dimensional flow structure of a wire-non-parallel plate push fan (PF) type EHD gas pump is measured by Particle Image Velocimetry (PIV). The dimensions of the EHD gas pump as well as the electrode configuration are similar to those presented by Tsubone et al [10], where the flow characteristics (pressure drop and flow velocity profiles at the pump exit) of the EHD gas pump were given. These flow characteristics allow only general conclusions regarding the generated flow at exit section of pump without understanding flow structure such as turbulent or re-circulating laminar inside pump.

Therefore, to understand the flow behavior in the EHD gas pump it is necessary to investigate in detail the velocity flow patterns near the flow driven electrodes. On the other hand, EHD flow vector maps in the central plane of EHD gas pump, was investigated by Kocik et al [11] using PIV by assuming flow is 2-dimensional. Kocik et al indicated that the generated flow patterns are turbulent and with distinct vortices. The vortices decrease with increasing operating voltage. The vortices formed inside the EHD gas pump have negative effect on pumping capabilities of the pump since the vortices may block and suppress the generated uni-directional flow. The effective pumping (24 L/min) was observed for PF-A type EHD pump at 14-15 kV, when the downstream or upstream vortices were scattered in the flow [11]. In order to study the vortices more detailed, the PIV measurement in the plane close to the side-wall of the EHD gas pump was performed in this work and compared with 2-dimentional numerical simulations.

Manuscript received on 9 October 2005, in final form 6 March 2009.

2 EXPERIMENTAL SET-UP

The EHD gas pump as shown in Figure 1 used in this experiment was a made of transparent acrylic plates having a thickness of 1 cm [11]. The internal length of the pump is 120 mm. Two engraved slits with 3° convergent angle were made in two sidewalls. Two acrylic plates covered with grounded metal tape electrodes could slide-in and off the engraved slits.

When these plates with grounded electrodes were placed in the slits, the cross sections of the EHD pump inlet and exit

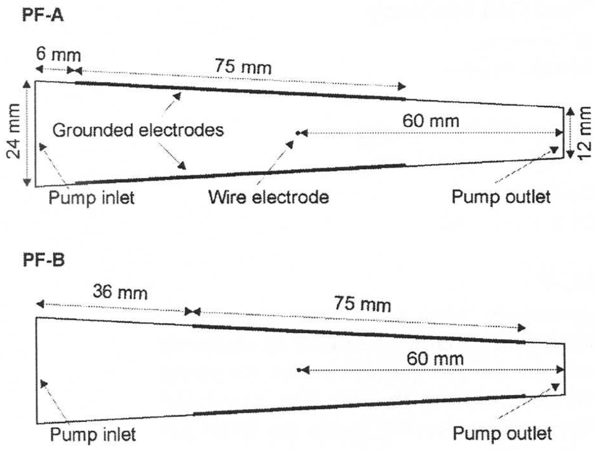

Figure 1. EHD gas pump dimensions and electrode geometry for different grounded plates locations PF-A and PF-B.

were of 35 mm x 24 mm and 35 mm x 12 mm, respectively. The grounded electrodes (75 mm x 35 mm) were made of aluminum tape of a thickness of 50 μm. They could be shifted along the acrylic plate base, changing their positions in respect to the wire discharge electrode. The discharge electrode was a stainless-steel wire of a diameter of 0.23 mm and width of 35 mm, stretched parallel to the grounded electrodes. The position of the corona wire electrode was always 60 mm from the EHD pump outlet. The wire electrode was stretched and kept tight to avoid sagging and corona induced vibration. Owing to it, the corona discharge was stable with low discharge current fluctuations, even when tuft spots were observed. Two positions of the grounded electrodes were set: 6 mm from the EHD pump inlet (the pump type called PF-A) and 36 mm from the EHD pump inlet (PF-B) (Fig.1). Two acrylic rectangular flow channel (11 cm x 14 cm x 40 cm) were connected to the inlet and exit sections of the EHD gas pump, then the both ends was connected by a plastic tube (ϕ=6 cm) to form a closed flow loop.

A dc high voltage was supplied to the wire electrode through a ballast resistor (10 MΩ) from a dc power supply (Spellman SL300). The applied voltage was measured using a high voltage probe.

The PIV measurements were carried out using a PIV equipment consisted of a twin second harmonic Nd-YAG laser system (λ=532 nm, pulse energy 50 mJ), imaging optics, two CCD cameras and PC computer equipped with Dantec Flow Manager software. A laser sheet, which defines the measuring plane, of a thickness of 1 mm, formed from the Nd-YAG laser beam by a cylindrical telescope, was introduced into the EHD gas pump. Cigarette smoke particles of mean diameters 0.2 μm [12] were used as seed tracers. The influence of the seed particles on the PIV measurement on EHD flow was minimized based on the selection of optimized particle size and seed particle density as proposed by Chang et al's model [13]. The PIV images of two observation cross sections were recorded by two Flow Sense M2 CCD cameras simultaneously. Each camera was capable of capturing two PIV images with minimum time separation of 2 μs. The CCD camera active element size was 1186 x 1600 pixels. The captured images were transmitted to the PC computer for digital analysis. The observation area of each camera was a rectangle of 4.5 cm x 6 cm.

The both observation cross sections were set as shown in Kocik et al [11], with 1 cm overlapping region. Two flow velocity vector maps were created, one for each observation cross section. Since both cameras recorded images simultaneously and the overlapping region was relatively wide, stitching the vector maps was possible. The stitching was made after averaging over 100 measurements into one flow velocity vector map which covered almost the whole length of the EHD gas pump. Using two cameras allowed obtaining images with higher resolution. Owing to that the vector maps were more detailed. Based on the measured vector maps, the flow streamlines (assuming 2-D) in the observation plane were calculated.

2 RESULTS

The time averaged corona current-voltage characteristics for PF-A and PF-B type EHD gas pumps for negative and positive applied voltage polarities are presented in Fig. 2. The corona onsets at above 6 kV of the applied voltage. For the voltages of 6-8 kV (corresponding to EHD number based on flow channel lower than 3 x 10^6), the EHD wake flow pattern (flow re-circulation) appeared near the corona wire, however no significant unidirectional flow could be observed. The unidirectional flow towards pump exit occurred for voltages

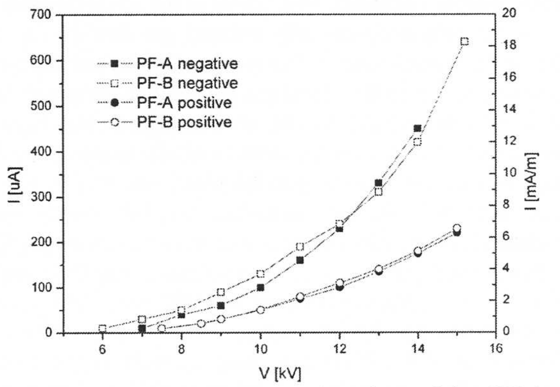

Figure 2. Time averaged corona current–voltage characteristics of PF-A and PF-B type EHD gas pumps for negative and positive applied voltage polarities.

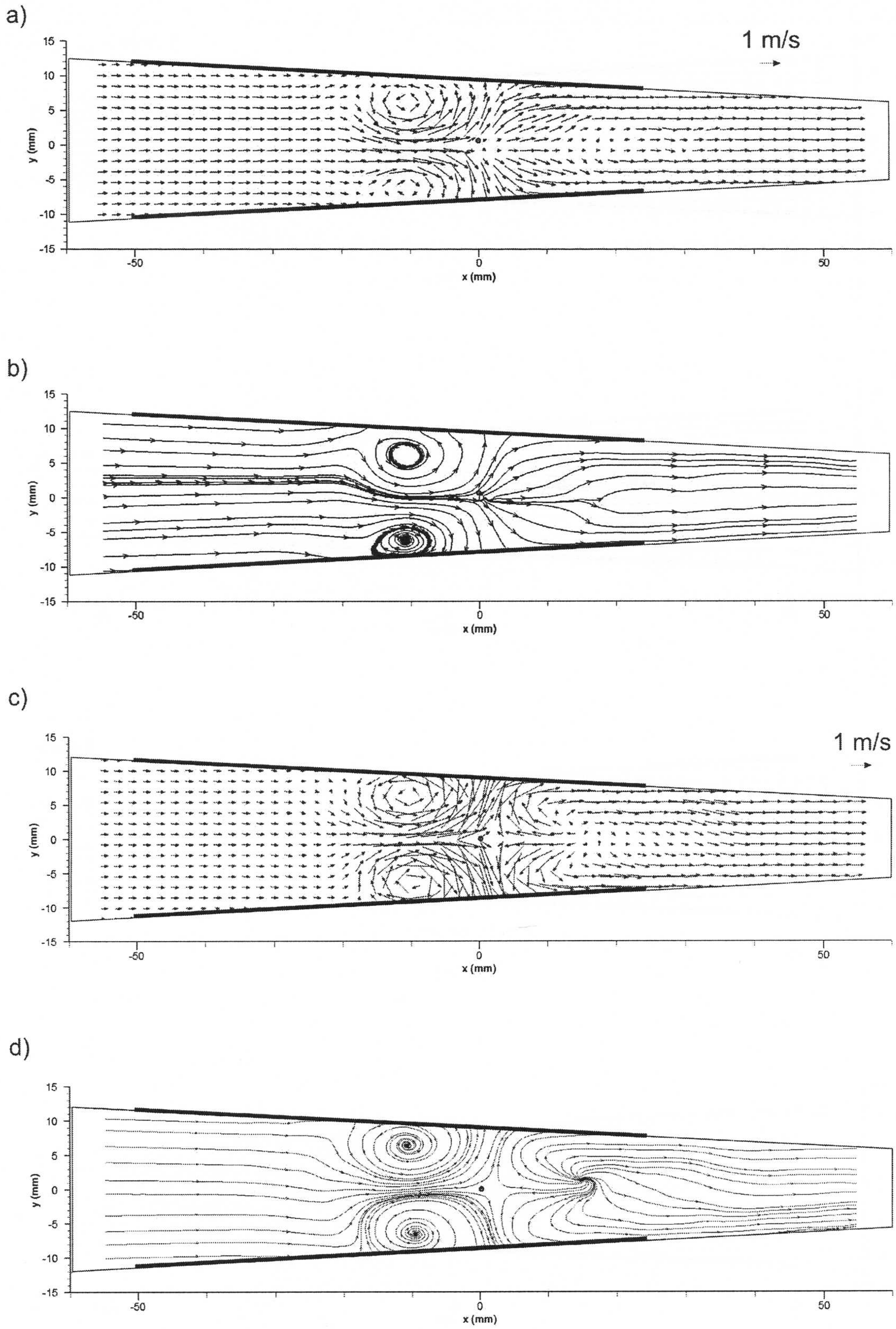

Figure 3. Flow velocity vector maps (a, c) and the corresponding flow streamlines (b, d) for PF-A type EHD gas pump for positive applied voltages of 15 kV and EHD number 1.6 x 10^7, measured in the plane passing along the center (a, b) and close to the side wall (c, d) of the gas pump.

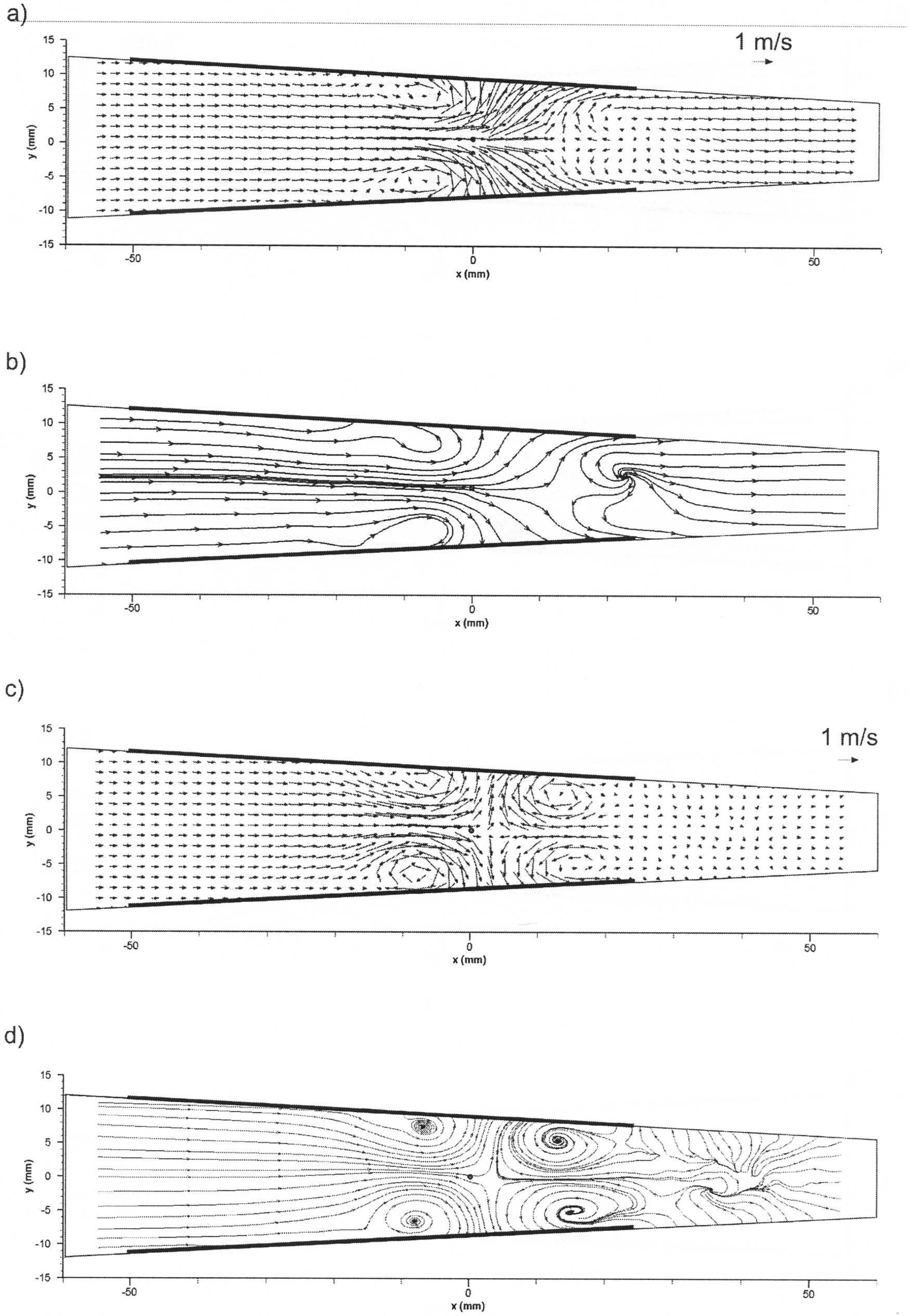

Figure 4. Flow velocity vector maps (a, c) and the corresponding flow streamlines (b, d) for PF-A type EHD gas pump for negative applied voltages of 14 kV and EHD Number 2.34 x 10^7, measured in the plane passing along the center (a, b) and close to the side wall (c, d) of the gas pump.

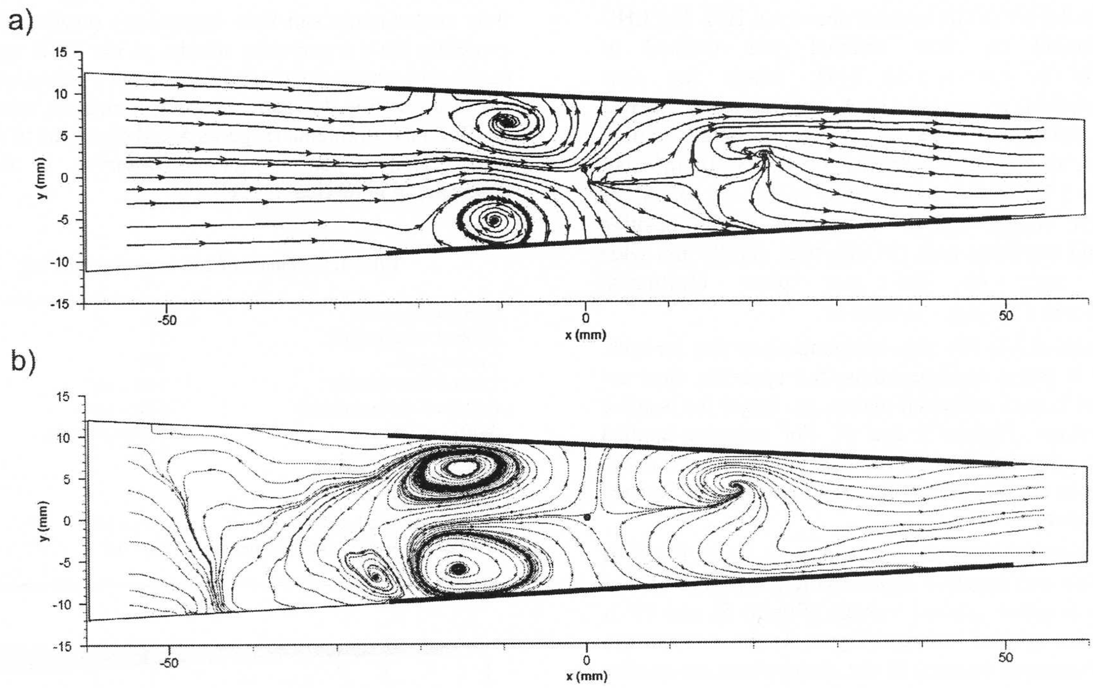

Figure 5. Flow streamlines for PF-B type EHD gas pump for positive applied voltages of 15 kV and EHD number 1.7 x 10^7, measured in the plane passing along the center (a) and close to the side wall (b) of the gas pump.

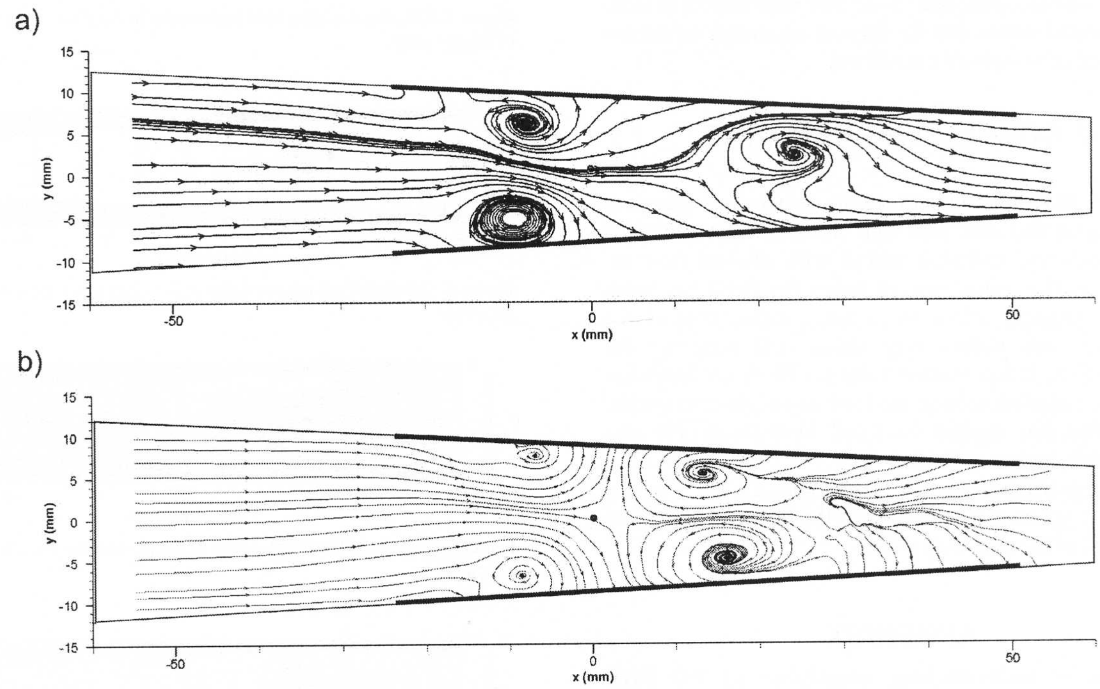

Figure 6. Flow streamlines for PF-B type EHD gas pump for negative applied voltages of 14 kV and EHD Number 2.2 x 10^7, measured in the plane passing along the center (a) and close to the side wall (b) of the gas pump.

higher than 8-9 kV (EHD number above 4 x 10^6). The EHD number based on flow channel was defined as $Ehd = I \times L^3 / (\nu^2 \times \rho \times \mu_i \times A)$ [14]; where the time average discharge current I A, characteristic length (average plate-plate distance in the discharge region) L = 18 mm, air kinematic viscosity $\nu = 1.57 \times 10^{-5}$ m^2/s, air density $\rho = 1.205$ kg/m^3, ion mobility $\mu_i = 2.7 \times 10^{-4}$ m^2/Vs for negative voltage and $\mu_i = 2 \times 10^{-4}$ m^2/Vs for positive voltage, and discharge area (35 mm long and 20 mm wide discharge area on the two plate electrodes) $A = 2 \times 35$ mm $\times$ 20 mm = 0.0014 m^2.

The results of 2-D PIV measurements show that for both, PF-A and B pump configurations, the upstream flow re-circulations in both measured planes, are larger for positive applied voltage (Figures 3 and 5). For negative applied voltage the upstream flow re-circulations are weaker in the plane close to the side-wall (Figures 4c, 4d, and 6b), caused by wall friction.

The downstream flow re-circulations are larger for PF-B configuration and negative applied voltage (Figure 6). For PF-B with positive applied voltage (Figure 5) and PF-A with negative applied voltage (Figure 4) the downstream flow re-circulations (wakes) in the center plane are smaller but still larger close to the side-wall. For PF-A with positive applied voltage (Figure 3) downstream wakes are very weak. By compared with 2-D numerical model (Appendix), the flow structure for the both PF-A and PF-B are more 3-dimentional due to the side wall and these side-wall generated wakes can be exist at up-stream of corona wire as well as asymmetric positions.

4 CONCLUDING REMARKS

The 2-D PIV measurement results at two flow planes at central region and near side wall show that the generated flow patterns are turbulent and/or with distinct flow re-circulations. The wakes formed inside the EHD gas pump may have negative effect on pumping capabilities of the pump since the wakes may block and suppress the generated flow. It was observed that for PF-A configuration and positive applied voltage the flow re-circulations are the smaller. This may explain the Kocik et al result [11] who showed that higher pumping was for PF-A type EHD pump. Comparison of the PIV results with a 2-D numerical modeling suggests that formation of the downstream wakes is the result of the side-wall effect.

APPENDIX

In order to understanding, mechanism of 3-D EHD induced flow, a typical 2-D numerical results for wire-non-parallel plate EHD gas pump presented by Chang et al [16] are shown in Figures 7 to 10 for comparison, where the results of modeling is based on Chun et al's model [15] with a modified boundary shape [16]. Parameters used in the numerical model are summarized in Table 1. The both flow vector maps and flow streamlines obtained from the modeling have a geometry similar to the PF-B type EHD pump, and results clearly show upstream vortices only. This suggests that the downstream wake formation, revealed by the PIV measurements (Figures 5 and 6), is due to the side-wall effect, which cannot be observed in the two-dimensional numerical model.

Table 1. Conditions of 2-D numerical modeling.

Inlet velocity (m/s)	0.0
Applied voltage (kV)	31
Current (μA)	150
Pressure drop (N/m2)	3.04×10^{-4}
Pressure Gradient (dp/dx)	5.06×10^{-4}
Wire position	Center of pump
Plate Inclined Angle	3 deg.
EHD number	
EHD no. based on flow channel	3.03×10^3
EHD no. based on wire diameter	9.8×10^6

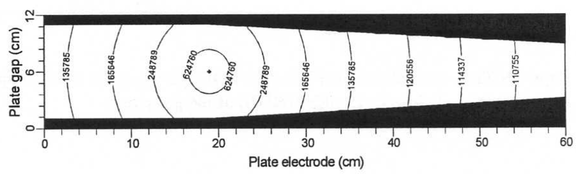

Figure 7. Calculated electric field distribution in the plane along the center of the gas pump.

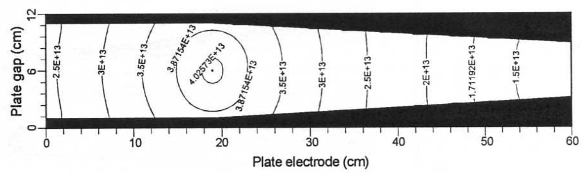

Figure 8. Calculated ion concentration in the plane along the center of the gas pump.

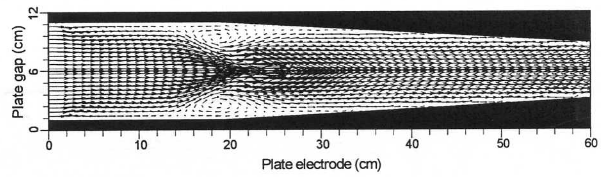

Figure 9. Calculated flow vector map in the plane along the center of the gas pump.

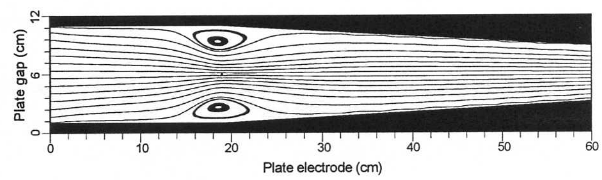

Figure 10. Calculated flow streamlines in the plane along the center of the gas pump.

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