EHD devices with parallel and in series spiked electrodes for air pumping and cleaning

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Abstract— Inhalation of submicron dust particles which can contain traces of toxic elements and metals can be harmful for human health. Thus, submicron dust particles removal from the air is very important and new devices for air cleaning are needed. We propose to use electrohydrodynamic (EHD) devices for air pumping and simultaneous dust particles removal. The aim of our investigations was to study the influence of the electrodes arrangement on the air pumping and the dust particle removal efficiencies. We studied EHD devices with parallel and in series arranged spiked electrodes. The flow velocity fields were measured by the Particle Image Velocimetry method and the submicron dust particles fractional number collection efficiency was determined.

I. INTRODUCTION

Due to the low weight the submicron dust particles (of diameter smaller than 1 µm) can float relatively long in the air. These particles can easily penetrate into human respiratory system. Furthermore, they often contain traces of toxic elements like sulphur and nitrogen oxides, ammonia and metals like mercury, arsenic and zinc [1]. Thus, submicron dust particles are potentially dangerous for human health. Therefore, rigorous standards for emission of fine dust particles has been introduced by the European Parliament [2] and in many countries around the world. These new standards forced development of devices for air cleaning. The collection efficiency of submicron dust particles in conventional electrostatic precipitators (ESPs) is still not satisfying [3-6]. Thus, ESPs improvement and new devices for fine dust particles removal are needed.

We propose to use an electrohydrodynamic (EHD) device for air pumping and simultaneous dust particles removal. Principle of operation of this device is similar to standard ESPs [7-8], which are used as dust particle collectors. However, in case of our EHD device external fan for primary flow generation is not needed. An airflow in this device is
induced by the EHD flow generated by the corona discharge [9-12]. When a strong electric field is generated between a spike of a high voltage electrode and a plate grounded electrode, a corona discharge occurs resulting in ionization of the gas molecules. An organized ion flux in an electric field initiate an ion-driven wind of neutral molecules (electrohydrodynamically induced gas flow is generated). The electrodes configuration results in asymmetrical electric field, what produces an unidirectional gas flow and causes EHD gas pumping.

In this paper we present two types of EHD devices, i.e. with parallel and in series spiked electrodes. We present the results of flow velocity field measurements which show the EHD flow patterns responsible for generation of unidirectional airflow in these EHD devices. The results of pumping rate and fractional collection efficiency measurements in the investigated EHD devices are also presented.

II. EXPERIMENTAL SET-UP

The experimental set-up for flow patterns investigations as well as for pumping rate and fractional collection efficiency measurements in the EHD device is presented in Fig. 1. It consisted of the apparatus for flow velocity field measurements by the 2-Dimensional Particle Image Velocimetry (2D PIV) method and a vane anemometer and an aerosol spectrometer for measurements of pumping rate and fractional concentration of dust particles in the EHD device powered by a high voltage power supply.

A. EHD Devices

The duct of the EHD device with parallel spiked electrodes (similar to that proposed by A. Katatani and A. Mizuno [13]) was made of a transparent acrylic box 600 mm long, 150 mm wide and 150 mm high (Fig. 2). Inside this box in the middle of its length, a frame for sustaining a spiked high voltage (HV) and a grounded electrodes was placed. In the frame two sets of the HV and the grounded electrodes made of 1 mm thick stainless-steel plate were mounted. The grounded electrodes having smooth edges and the spiked HV electrodes were 124 mm wide and 150 mm long. The one edge of each HV electrode was ended with 20 spikes. The spikes were 10 mm long and the distance between
neighbouring spike tips was 6 mm. The frame sustaining electrodes allowed mounting the set of HV and the grounded electrodes one above another, thus forming a multi-layer electrode arrangement. The set of the electrodes consisted of 3 HV electrodes and 4 grounded electrodes. When the DC high voltage was applied to the electrodes a corona discharge started and the unidirectional airflow in the EHD device was induced. As we showed in [14] the maximum pumping rate of this device was obtained when the distance $G$ between neighbouring electrodes was 20 mm and the shift $X$ (in x direction) between the edges of these electrodes was 50 mm. Thus, in the present studies we chose such electrodes configuration (with $G = 20$ mm and $X = 50$ mm) to achieve high pumping rate of the EHD device.

![Fig. 2. Scheme of the EHD device with parallel spiked electrodes](image)

The EHD device with in series spiked electrodes consisted of a transparent acrylic box (1600 mm long, 200 mm wide and 100 mm high) with two smooth stainless-steel plate electrodes (1100 mm $\times$ 200 mm) placed at the top and bottom of the device and four stainless-steel spiked electrodes mounted in the plane in the middle between the plate electrodes (Fig. 3). Each spiked electrode had 6 spikes on the one side. These electrodes were 200 mm long, 1 mm thick and 25 mm wide. The distance between consecutive HV electrodes was 150 mm. The distance between the plate electrodes and the spiked electrodes was 50 mm. The plate electrodes were grounded whereas DC high voltage was applied to the spiked electrodes. When the HV was applied the corona discharge started from the spike tips of these electrodes and a unidirectional flow in the EHD device was induced.

![Fig. 3. Scheme of the EHD device with in series spiked electrodes](image)
At the inlet and the outlet of both EHD devices (with parallel and in series spiked electrodes) the shape adapters were mounted. The inlet adapter transformed from a circular cross section of a diameter of 160 mm to a rectangular cross section (as needed to connect with the EHD device duct). The adapter at the outlet of the EHD device transformed from a rectangular cross section to the circular (diameter of 160 mm). The inlet and outlet adapters were 270 mm long. During the collection efficiency measurements in the inlet adapter, coaxially with its circular section, a vane anemometer (Delta Ohm HD2103.2) probe was placed. The probe diameter was 60 mm. The anemometer measured the velocity of the airflow induced in the EHD devices. The vane anemometer was removed during the flow velocity fields measurements because its rotating blades would disturb the flow structure in the EHD device.

B. Power Supply

The negative DC high voltage was supplied to the spiked electrodes by a Spellman SL300 high voltage supply. In the case of the EHD device with parallel spiked electrodes the set of spiked electrodes was supplied through a ballast resistor $R = 3.33 \, \text{M}\Omega$. In the case of the EHD device with in series spiked electrodes each spiked electrode was supplied through a ballast resistor $R = 10 \, \text{M}\Omega$. In both cases the voltage and the average discharge current were measured by the meters installed on the high voltage supply output. Basing on the measured values the voltage applied to the spiked electrodes and then the discharge power were calculated.

C. PIV System

The flow velocity fields in the EHD devices were measured using PIV method. The 2D PIV system consisted of a double Nd:YAG laser system ($\lambda = 532$ nm), a cylindrical telescope, a CCD camera and a PC computer. The PIV investigations were carried out in the plane fixed by a laser sheet shaped by the cylindrical telescope. The laser sheet was introduced in the centre of the EHD device duct, perpendicularly to the plate grounded electrodes. The pairs of images (made at a known time intervals) of the seeding particles dissipating the laser light were recorded by the FlowSense M2 camera. The CCD camera sensor size was 1600 pixels $\times$ 1186 pixels. In the case of the EHD device with parallel spiked electrodes the camera observed area around and behind the spikes of only two discharge electrodes. In the case of the EHD device with in series spiked electrodes the camera observed area around the discharge electrode number 2 (Fig. 3).

For every investigated case 100 pairs of PIV instantaneous images of the flow in the EHD device duct were taken and transmitted to the PC computer for a digital analysis. An adaptive cross-correlation algorithm was applied to the set of these 100 image pairs to compute 100 instantaneous flow velocity fields. The interrogation window for the cross-correlation procedure was 32 pixels $\times$ 16 pixels (horizontal $\times$ vertical). The overlap between neighbouring interrogation windows was 25% which was sufficient for right tracing the particles moving from one interrogation window to the neighbouring one. Finally, basing on the 100 instantaneous flow velocity fields a time-averaged flow velocity field was calculated. From the time-averaged flow velocity field the apparent flow streamlines were calculated.
D. Collection Efficiency Measurements

The EHD device was tested in a laboratory room having dimensions of 5.8 m × 4.6 m × 2.9 m. The air in the laboratory was polluted with an incense smoke. The fractional concentration of dust particles suspended in the air in the laboratory was measured using an optical aerosol spectrometer GRIMM 1.109 (particles size scale ranging from 0.25 µm to 32 µm in 31 size channels, maximum particle concentration 2 million per litre).

The measurements of the dust particles fractional concentration were carried out on the inlet and the outlet of the EHD device. Every measure lasts 4 minutes; 1 minute at the inlet then 2 minutes at the outlet and again 1 minute at the inlet. In order to reduce the statistical fluctuations of particles concentration at least 10 measures were performed for specific operating parameters of the EHD device. Basing on the results of these 10 measures the average fractional particle concentration was calculated for the inlet and outlet air and then the fractional particle collection efficiency was computed using equation:

\[
\eta_f\left(d_p\right) = \left[1 - \frac{c_{\text{out}}\left(d_p\right)}{c_{\text{in}}\left(d_p\right)}\right] \cdot 100\%
\]

where: \(c_{\text{out}}(d_p)\) and \(c_{\text{in}}(d_p)\) are the average fractional particle concentrations respectively at the outlet and at the inlet of the EHD device.

III. RESULTS

The current-voltage characteristics for the EHD devices with parallel and in series spiked electrodes are presented in Figs. 4a and 4b respectively. For both EHD devices the discharge current continuously increased with increasing applied voltage. The discharge current increased faster for the device with parallel spiked electrodes. It is most likely caused by the lower distance between the discharge and the grounded electrodes (20 mm for device with parallel and 50 mm for device with in series electrodes). In the EHD device with parallel electrodes the electron avalanches primarily constitute the discharge current, while slower negative ions determine relatively lower discharge current in the EHD device with in series electrodes.

Fig. 4. Current-voltage characteristics for the EHD device with (a) parallel and (b) in series spiked electrodes. Negative voltage polarity
A vector map showing time-averaged flow velocity field measured in the EHD device with in series spiked electrodes is presented in Fig. 5. As it can be seen, the jet-like flow was generated near the spike of the discharge electrode and it induced an unidirectional flow through the EHD device duct. However, the air was sucked by the jet not only from the inlet of the EHD device, but also from its interior, i.e. from the neighbourhood of the plate electrodes. As a consequence, only a part of the air was directed to the EHD device outlet. The remaining air revolves in the recirculation areas. Individual flows generated by the consecutive discharges (in vicinity of consecutive HV spiked electrodes) accumulate and a significant net unidirectional airflow in the EHD device duct could be induced.

The example of the time-averaged flow velocity field measured in the EHD device with parallel electrodes is presented in Fig. 6. As it can be seen, also in this case behind the spikes of the HV electrodes the jet-like flow was generated. This jet-like flow is responsible for formation of unidirectional flow through the EHD device, but it also induces recirculation of the air between the HV and the grounded electrodes. Resultant flow structure is clearly visible when observing the flows streamlines (presented in Fig. 7) calculated basing on the time-averaged flow velocity field. As we showed in [14] recirculation of the air in the EHD device with parallel spiked electrodes is capable of hindering the induction of the unidirectional air flow.

Experimental results obtained during the dust particles collection efficiency measurements are presented below. The average velocities of the induced unidirectional air flow measured using the vane anemometer installed in the inlet adapter (and calculated on its basis the average flow rate) versus the average discharge current for both investigated EHD devices are presented in Fig. 8. It is clearly seen in this figure, that the velocity of the unidirectional air flow was about 2 times higher for the EHD device with in series spiked electrodes than for the EHD device with parallel electrodes. The maximum velocity of the unidirectional air flow induced in the EHD device with in series spiked electrodes was about 2 m/s, what means that in this case the pumping rate was 0.04 m$^3$/s (inlet adapter cross section 0.02 m$^2$). In the case of the EHD device with parallel spiked electrodes the maximum velocity of the induced unidirectional air flow was about 1 m/s, i.e. flow rate 0.02 m$^3$/s.
Fig. 6. Time-averaged flow velocity field measured in the EHD device with parallel spiked electrodes. The negative high voltage applied to the spiked electrodes was 15 kV.

Fig. 7. Apparent flow streamlines in the EHD device with parallel spiked electrodes. The negative high voltage applied to the spiked electrodes was 15 kV.
Fig. 8. Average velocity (and flow rate) of the unidirectional air flow induced in the EHD devices with parallel and in series spiked electrodes

The size distribution of the dust particles suspended in the laboratory air (polluted with the incense smoke) is shown in Fig. 9. Presented values were normalized to the total number of measured dust particles. It was calculated that 99.9% of the measured dust particles had a diameter smaller than 1 µm. The normalized size distribution of the dust particles remained unchanged during the fractional particle number collection efficiency measurements for the EHD devices with parallel and in series spiked electrodes. Thus, in this paper we present the results for submicron particles measured in the first 11 channels of used aerosol spectrometer (dust particles diameter from 0.25 µm to 1 µm).

Fig. 9. Normalized fractional concentration of dust particles suspended in the laboratory air

The results of fractional collection efficiency measurements in the EHD device with parallel and in series spiked electrodes are shown in Figs. 10 and 11 respectively. As it can be seen in these figures, the fractional collection efficiency of dust particles increases with increasing applied voltage and with increasing diameter of dust particles. It is due to the fact that the net charge of dust particles and the Coulomb force acting on them increases with increasing diameter of dust particles and applied voltage (field charging mechanism) [15].
Comparing the fractional collection efficiencies measured for the investigated EHD devices (Figs. 10 and 11), it can be seen, that the dust particles fractional collection efficiency was about 20% - 30% higher in the case of the EHD device with in series spiked electrodes than for the EHD device with parallel spiked electrodes. It is probably due to the bigger net charge that could be collected by individual dust particles which were repeatedly passing through the consecutive discharge regions of the EHD device with in series spiked electrodes. Moreover, the collecting area (the active area on the grounded electrodes – an important parameter in electrostatic precipitation) in the EHD device with in
series spiked electrodes was larger than in the EHD device with parallel spiked electrodes.

**IV. SUMMARY AND CONCLUSION**

The 2D PIV investigations of EHD flow in the EHD devices with parallel and in series spiked electrodes were performed. Our investigations revealed generation of the complex EHD flow near the spiked electrodes. The obtained results showed that in both EHD devices the EHD flow induced significant recirculation areas between the spiked electrodes and the grounded electrodes. Reducing the size of these recirculation regions should be beneficial for inducing higher velocity of unidirectional air flow in the EHD device, i.e. for efficient gas pumping.

The maximum flow rate of 0.04 m$^3$/s was obtained in the case of the EHD device with in series spiked electrodes. This is enough to meet the ventilation rate standard for 8 persons (0.005 m$^3$/s for one person) in non smoking areas as an office (ANSI/ASHRAE Standard 62.1-2007 “Ventilation for Acceptable Indoor Air Quality” [16]). The maximum flow rate for the EHD device with parallel spiked electrodes was about 2 times lower than in the case of the EHD device with in series spiked electrodes. However, it should be noticed that this lower value for device with parallel electrodes was obtained for the discharge power of 16.8 W, while 23.5 W was needed for supplying device with in series electrodes.

The fractional collection efficiency measurements showed that the investigated EHD devices were capable of collecting submicron dust particles with a relatively high effectiveness. Especially the EHD device with in series spiked electrodes was very efficient (the fractional collection efficiency of dust particles was from about 60% for the particles of the diameter from 0.25 µm to 0.28 µm up to 80% for the particles of the diameter from 0.8 µm to 1 µm). The collection efficiency for the EHD device with parallel spiked electrodes was about 20% - 30% lower.

Lower induced unidirectional air flow and dust particles collection efficiency in the EHD device with parallel electrodes were obtained using lower discharge power than used in the EHD device with in series spiked electrodes. Moreover, investigated device with parallel electrodes was much shorter than that with in series electrodes. Thus, placing for example two more sets of the HV and the grounded electrodes in the EHD device with parallel electrodes would greatly increase the pumping rate and in this way the total number of collected dust particles. However, the particles collection efficiency calculated as the ratio of the precipitated particles to the particles at the device inlet would probably not change significantly. To obtain high collection efficiency a number of precipitation regions placed in series is needed. In such way, the dust particles not precipitated in the first region can be collected in the next one (especially that have some initial charge when inflowing). Therefore, one can guess that some combination of parallel sets of electrodes placed one after another (i.e. in series) is optimal from pumping rate, collection efficiency and device size points of view. Considering simple construction, lack of moving parts and relatively high efficiency of submicron dust particles collection investigated EHD devices can be useful for air pumping and cleaning.
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