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Electrohydrodynamic gas flow in a positive polarity wire-plate electrostatic precipitator and the related dust particle collection efficiency

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Abstract

In this paper, the results of the particle image velocimetry measurements of the flow velocity fields in an intermediate spacing wire-to-plate type electrostatic precipitator (ESP) with a single positive polarity wire electrode are presented. The observation plane was placed perpendicular to the wire electrode at its half-length. The investigation showed significant influence of the electric field and charge on the flow patterns in the intermediate spacing ESP under an extreme large electrohydrodynamic (EHD) number. The EHD forces cause the formation of strong vortex pairs in the upstream and downstream ESP regions for $\mathrm{Ehd}/Re^2 > 1$.

Keywords: Electrostatic precipitator; Corona discharge; EHD flow; PIV; Flow measurement

1. Introduction

The motion and precipitation of particles in the duct of an electrostatic precipitator (ESP) depend on the dust-particle properties, electric field, space charge and gas-flow field. It has been shown [1,2] that a significant interaction between these factors exists, resulting in considerable turbulent flow structures in the volume between the stressed and collecting electrodes. However, it is not yet clear whether these turbulent flow structures advance or deteriorate the fine particle precipitation process. To elucidate the influence of the electrically generated flow disturbances in the case of a high resistivity cleaning process in intermediate spacing ESPs, more experimental investigations are needed.

Recently, the method of particle image velocimetry (PIV) [3] was introduced for instantaneous measurement of the flow velocity field, including the turbulence, in large cross-sections of the flow. In particular, the PIV technique has been used for investigating the structure of electrohydrodynamically induced secondary flow in ESPs [4–7].

In this paper, the results of PIV measurements of the flow velocity fields for large electrohydrodynamic (EHD) numbers in an intermediate spaced wire-plate ESP with positive polarity wire are presented.

2. Experimental setup

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

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measuring method and schematics of the apparatus were described in detail in reference [4].

The ESP had a single wire electrode (diameter 1 mm, length 200 mm) placed in the middle of the ESP between two grounded, stainless steel plate electrodes. The plate electrode widths were 200 mm each, while the plate-to-plate electrode spacing was 100 mm. The PIV measurements were carried out in a plane placed perpendicular to the wire electrode at its half-length.

Airflow seeded with fine TiO_2 particles (size less than 1 μm) was blown along the reactor duct with an average velocity that varied from 0 to 1.0 m/s. The positive voltage applied to the wire electrode through a 10-MΩ resistor was varied between 0 and 35 kV. The Reynolds and EHD numbers varied from 0 to 6000, and from 0 to 2×10^8, respectively [8].

The flow velocity field maps (100 × 400 mm) presented in this paper are composed of four adjacent velocity fields (100 × 100 mm each). All the velocity fields presented resulted from the averaging of 100 measurements; thus each velocity map shown is time averaged.

3. Results

The flow velocity field patterns and corresponding flow streamlines in the intermediate spacing wire-plate type ESP are shown in Fig. 1 for the case of no primary flow ($U_0 = 0\,\mathrm{m/s}$), and in Fig. 2 for a primary flow velocity of 0.3 m/s. Figs. 1a and 2a show the flow velocity field patterns and the corresponding flow streamlines in the ESP without the primary flow ($Re = 0$; $\mathrm{Ehd}/Re^2 \to \infty$) for a time-averaged discharge current of value $I = 150\,\mu\mathrm{A}$. Two pairs of strong vortexes of the secondary flow are clearly visible in both the upstream and downstream regions of the corona wire. The flow in the vortexes moves from the wire electrode almost perpendicularly towards the plate electrodes, then along the plate electrodes, turning back towards the wire electrode at a distance of about 120–130 mm from the wire electrode. The secondary flow vortexes are caused by the EHD forces resulting from the applied electric field and space charge formed. The apparent asymmetry in the velocity field pattern shown in Fig. 1, usually not expected for $U_0 = 0\,\mathrm{m/s}$ and $\mathrm{Ehd}/Re^2 \to \infty$, might not result from the imperfection of the electrode and duct arrangement only. Rather, it might be a result of the stochastic onset of an asymmetric, unsteady turbulent flow. This effect was not removed in the relatively short image averaging process (over 40 s).

Figs. 1b and 2b show the flow patterns and the corresponding streamlines in the ESP at a primary flow velocity of 0.3 m/s and total discharge current $I = 150\,\mu\mathrm{A}$. At this velocity, the Reynolds number ($Re = U_0 L/\nu$) is equal to 2000, the Ehd number ($\mathrm{Ehd} = L^3 I/\mu_i \rho \nu^2 A$) is equal to 2×10^8, and the ratio Ehd/Re^2 is equal to 50 [8]. The parameters used to calculate Re and

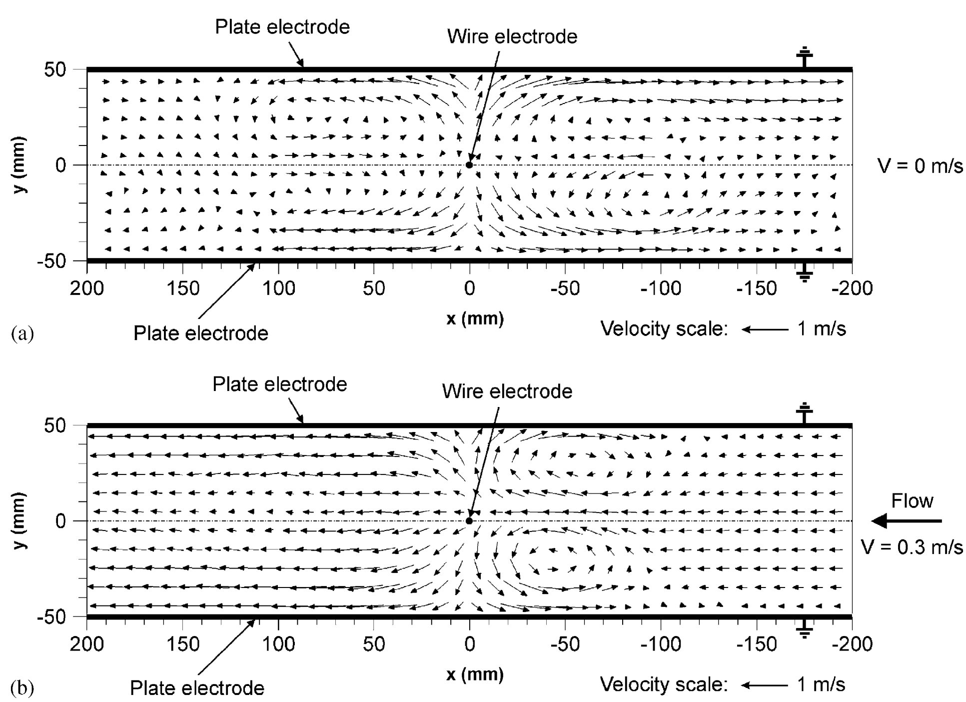

Fig. 1. Flow velocity field patterns in the wire-to-plate type ESP. The primary flow velocities: (a) 0 m/s ($Re = 0$), (b) 0.3 m/s ($Re = 2000$). Positive voltage varied from 30 to 32 kV to maintain discharge current at 150 μA ($\mathrm{Ehd} = 2 \times 10^8$).

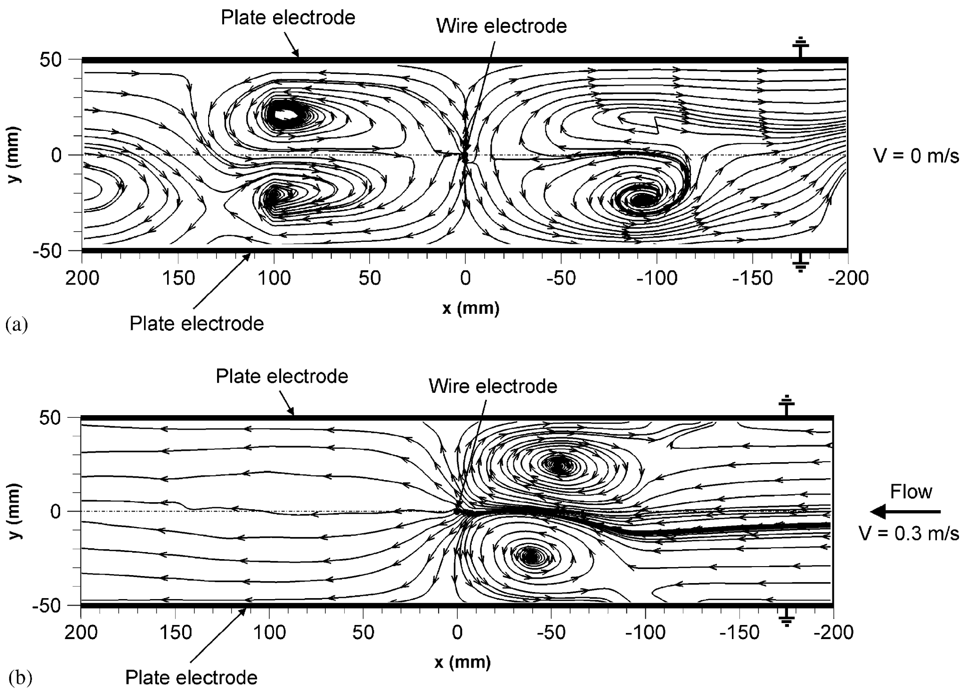

Fig. 2. Flow streamlines in the wire-to-plate type ESP. The primary flow velocities: (a) 0 m/s ($Re = 0$), (b) 0.3 m/s ($Re = 2000$). Positive voltage varied from 30 to 32 kV to maintain discharge current at 150 μA (Ehd $= 2 \times 10^8$).

Ehd consisted of the primary flow velocity $U_0 = 0.3\,\mathrm{m/s}$, characteristic length (plate-to-plate distance) $L = 0.1\,\mathrm{m}$, kinematic air viscosity $\nu = 15 \times 10^{-6}\,\mathrm{m^2/s}$, discharge current $I = 150\,\mu\mathrm{A}$, mobility of $N_2O_3^+$ ions in air: $\mu_i = 0.646 \times 10^{-4}\,\mathrm{m^2/V\,s}$, air density $\rho = 1.205\,\mathrm{kg/m^3}$, and the discharge area (i.e., the 100 mm-wide region around the wire electrode) of value $A = 2 \times 0.1\,\mathrm{m} \times 0.2\,\mathrm{m} = 0.04\,\mathrm{m^2}$. Because Ehd/$Re^2 \gg 1$, the electric force dominates over the inertial force, thus disturbing heavily the primary flow, as seen in Figs. 1b and 2b.

As seen from Figs. 1 and 2, for large Ehd/Re^2 the regular and stable vortexes are formed in the upstream region of the corona wire (the so-called forward wakes). They are smaller than those for the case without the primary flow. In addition, the forward wake centers for large Ehd/Re^2 are closer to the wire electrode (about 50 mm). The forward wakes block the primary flow along the plate electrodes and increase velocity near the ESP axis. This type of forward wake was not observed in ESPs of moderate Ehd/Re^2 number [1], where the vortexes are located near the plate electrodes above and below the wire electrode. As seen in Figs. 1 and 2, the gas flow turns towards the plate electrodes near the wire electrode (i.e. in the discharge region), due to the strong EHD secondary flow at this location. In the downstream region of the ESP, the flow pattern is regular and directed in accordance with the primary flow direction. Due to the strong EHD secondary flow towards the plate electrodes, the velocity of the gas flow near the plate electrodes doubles the flow velocity on the ESP axis.

4. Dust particle collection efficiency

The transport of the dust particles (diameter $d_p < 1\,\mu\mathrm{m}$) can be described by the dimensionless particle transport equations [8,9] as follows:

$$\frac{Re\,Sc}{2}\vec{u}_g\tilde{\nabla}n_d \pm F_E\tilde{\nabla}(n_d\vec{\xi}) - \tilde{\nabla}^2 n_d = 0,$$

where Re is the Reynolds number, Sc is the Schmidt number, $\vec{u}_g$ is the dimensionless gas velocity vector, n_d is the dimensionless dust particle number density, F_E is the electric field number, and $\vec{\xi}$ is the dimensionless electric field vector. Hence, the EHD-induced secondary flow becomes dominant when $Re\ Sc/F_E < 1$ [10]. The McMaster Electrostatic Precipitator (MESP) code simulation [10] shows that particles of diameter $0.1\,\mu\mathrm{m} < d_p < 1\,\mu\mathrm{m}$ are most significantly influenced by the EHD flow. Therefore, for the flow region near the corona wire, contamination of the wire occurs due to the flow between the two forward EHD wakes. On the other hand, for the flow region above and below the corona wire, dust particle collection may be enhanced due to the attachment of the EHD wake to the ESP collection electrode.

5. Concluding remarks

In this paper, the results of PIV measurements of the flow velocity fields in an intermediate spacing wire-plate ESP with positive wire polarity are presented.

The measurements show a significant influence of the EHD forces on the flow patterns because of the extremely large EHD number. The EHD forces cause the formation of vortex pairs in the upstream and downstream regions of the corona wire. The primary flow pushes and compresses the upstream vortex pair. The higher the primary flow velocity, the smaller are the upstream vortexes. The strong upstream vortexes cause blocking of the primary gas flow near both plate electrodes and cause it to move along the central part of the ESP. In the downstream region, the pair of vortexes, clearly seen at a primary flow velocity of $U_0 = 0\,\mathrm{m/s}$, are scattered by the primary flow. Due to the strong EHD secondary flow towards the plate electrodes, the velocity of the gas near the plate electrodes in the downstream region is double that on the ESP axis. This means that the majority of the gas mass moves along the plate electrodes in the downstream region. The influence of the EHD secondary flow on the collection of the dust particles is significant at large Ehd/Re^2 ratio existing in this type of ESP.

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