Numerical Modeling of the Electrohydrodynamics in a Hybrid Particulate Collector

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Abstract: The specific gas flow influenced by the electrical field in the electrostatic precipitator (ESP) is called electrohydrodynamic (EHD) flow. The hybrid particulate collector (HPC) is a hybrid of the ESP and the baghouse in a unique approach combining the best features of both. The bags are placed between two perforated collection plates. The HPC is a very compact and high efficiency system. In this paper, numerical modeling of the three-dimensional EHD flow in a hybrid particulate collector (HPC) is presented. An unstructured finite volume method (FVM) was developed to solve the Poisson's electrical equation and the current continuity equation within the collector. The Fluent code was used to solve the fluid N-S equations and the RNG $k-\varepsilon$ turbulent model equations with considering the electrical body force. The numerical results show that the EHD flow can produce strong recirculation in the hybrid collector. Different from the ESP, the electric field has still strong influence on the gas flow when the EHD number below one.

Keywords: Electrostatic precipitator, Hybrid particulate collector, Electrohydrodynamic, Electric wind, Turbulence model

1 INTRODUCTION

The electrostatic precipitator (ESP) is a widely used device to separate fine particles from the flue gas by using the electrostatic forces [1]. In the ESP, gas flows between grounded parallel plates of sheet metal and high voltage corona discharge electrodes. Due to the high voltage applied to the discharge electrodes, the air between the plates and the electrodes breaks down electrically, known as "corona discharge". The corona-generated ions make the particles that pass through the precipitator charged by many mechanisms concurrently. Then the charged particles are driven to the collecting plates by the electric field and are deposited on the plates. There exist two types of gas flow in the ESP, i.e. the primary flow and the secondary flow. The primary flow is the gas flow through the precipitator, called cross-flow. The secondary flow is the flow field caused by the electrical field, often called 'electric wind'. This fluid dynamics coupled with the electrostatic field is called electrohrdrodynamics (EHD). Much experimental and numerical works have been carried out to study the influences of the EHD on the ESP's performance [2-12]. The EHD can produce the secondary recycle flow [2] and the vertex flow [3], both of which are studied in detail experimentally in Ref. [5]. The secondary flow tends to reduce the transport of the dust particles towards the plate upstream of the corona wire and to enhance that downstream of the corona wire, and influences the dust particle collection [4]. Besides, the electric wind increases the flow turbulence intensity and diminishes the collecting efficiency [6, 7]. But the dominance of the EHD flow in wire-plate ESP is very sensitive to the magnitude of the inlet flow velocity and the discharge current [8-11]. When the inlet flow velocity is higher enough, the effect of the electric wind is negligible. Only when the inlet flow velocity becomes smaller, the electric wind becomes pronounced and has a significant influence on the flow field and the performance. Moreover, the EHD flow has stronger influences on the smaller particles, especially the ultrafine particles [12].

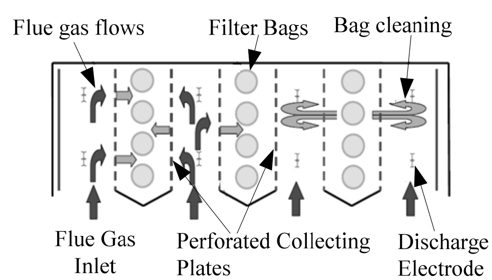


Fig. 1 The sketch of the AHPC

The advanced hybrid particulate collector (AHPC) is a new type precipitator that combines the ESP and the baghouse together in a unique approach [13], as shown in figure 1. The bags and the ESP are placed in the same housing, working synergically both in the particulate collection and in the dust cleaning. The AHPC provides ultrahigh collection efficiency, overcoming the problem of excessive fine-particle emission with conventional ESPs, and it solves the problem of re-entrainment and re-collection of dust in conventional baghouses. The experimental works show that the AHPC can achieve the particulate collection efficiencies of 99.99% for particle sizes from 0.01 μm to 50 μm. For economical consideration, the AHPC can work at a much higher air-to-cloth (A/C) ratio with respect to the conventional fabric filters. The flue gas first flows into the ESP zone to remove the most particles (about 90% by mass), and then goes through the holes in the perforated plates into the fabric filtration zone to remove the left particles. Hence, the pressure drop through the fabric filters can be very low which means that the fabric filters have longer life. The dust accumulated on the collection plates and filtration surfaces must be removed periodically and transferred to the hopper. In the AHPC, there is important synergism between the ESP and the fabric filters in the dust cleaning. When the fabric bags are cleaned with a reverse pulse of pressurized air, the larger agglomerated may fall directly into the hopper, however, much of the dust is re-entrained into particles too small to fall to the hopper. These small particles are agglomerated into larger particles than are originally collected on the bags. Different from the conventional fabric filters that these particles are recollected on the bags, they are propelled into the ESP zone to be charged and collected in the AHPC. Similarly, the re-entrainment particles generated during the ESP zone plates rapping will be collected in the filtration zone.

In the present study, a three-dimensional EHD simulation was carried out in order to investigate the formation of the electric wind in a model hybrid particulate collector (HPC). The HPC is shown in figure 2. Beginning with this introduction as Section 1, the paper is organized as follows. Section 2 gives the mathematical models of the electric field and the EHD flow. The numerical results and discussions are described in Section 3. And Section 4 presents the conclusions.

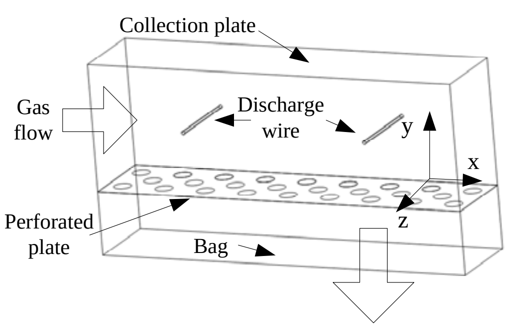


Fig. 2 The sketch of the HPC

2 MATHEMATICAL MODELS AND NUMERICAL METHODS

2.1 Models for the Electric Field

In the absence of particles, neglecting the transport gas velocity and by the assumptions described in Lei [12], the governing equations of the electric potential and the space-charge-density are written as

$$\frac{\partial}{\partial x_k}\left(\frac{\partial \mathrm{V}}{\partial x_k}\right) = -\rho_{ion}/\varepsilon \tag{1}$$

$$\frac{\partial \mathrm{J}_k}{\partial x_k} = 0 \tag{2}$$

where V is the electric potential, ρ_{ion} is the space charge density, ε is the air permittivity (8.85×10^{-12} $\mathrm{C^2/N\,m^2}$), $\boldsymbol{J}_k$ is the current density.

The electric intensity $\boldsymbol{E}$ and electric current density $\boldsymbol{J}$ are related to the electric potential and the space-charge density by

$$\boldsymbol{E} = -\nabla \mathrm{V} \tag{3}$$

$$\boldsymbol{J} = \rho_{ion} K \boldsymbol{E} \tag{4}$$

where K is the ion mobility.

The boundary conditions proposed in McDonald et al. [14] are used here.

2.2 Models for the EHD Flow Field

The flow in the HPC is turbulent, three-dimensional and influenced by the electric field and the ion current. A number of studies were carried out calculating the EHD flow field by solving the time-averaged Navier-Stokes equations with a turbulence model [8-12]. The gas behavior can be described by means of the mass and momentum equations with considering the electric body force. Among the turbulence models, the standard $\kappa-\varepsilon$ model [15] seems to be the most commonly used and the most efficient to study the EHD flow [8, 10]. But for the HPC, the streamlines of the gas flow has strong curvature. Thus, the RNG $\kappa-\varepsilon$ model is used as the turbulence model [16].

The HPC includes three types of fluid boundaries: the velocity inlet, the solid wall, and the symmetry for the bag.

3 RESULTS AND DISCUSSION

In the HPC, the distance between the two plates is 140 mm and the distance between the perforated plate and the bag is 70 mm. The HPC contains two discharge wires, whose radius is 0.3 mm and the space distance is 210 mm. The length is 420 mm, and the width is 96 mm. The perforated plate has 26 holes, each of which is a 19 mm circle. The environmental pressure is about 1 bar, and the temperature is 298 K.

3.1 Electric Conditions

Fig. 4(a) is the V-I characteristic of the HPC.

The EHD number E_{hd} , which is the ratio of the electrical body force to the inertial body force, is defined as follows [17]:

$$E_{hd} = \frac{I_0 L^3}{\rho_f v_f^2 K A} \tag{6}$$

where I_0 is the reference current (A), ρ_f is the air density (1.18 kg/m^3), L is the characteristic length (0.14 m), v_f is fluid kinematic viscosity (1.56e^{-5} m^2/s), A is the discharge area (420 mm long and 96 mm width) 0.0403 m^2, the ion mobility K is 1.82 e^{-4} m^2/V s (negative corona).

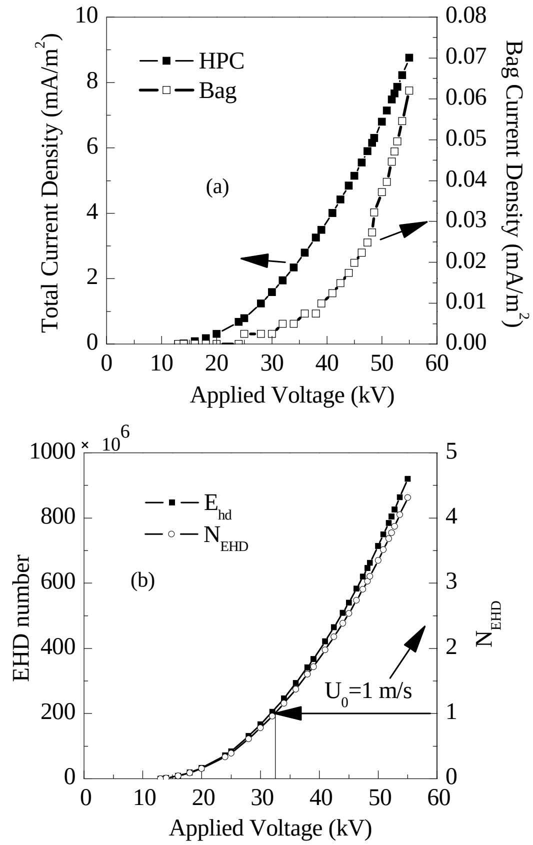


Fig. 4 The experimental V-I characteristic (a) and the EHD number characteristic curve (b) of the HPC

The importance of the EHD induced secondary flow can be scaled by the ration of the EHD number to the Reynolds number squared:

$$N_{\mathrm{EHD}} = E_{\mathrm{hd}} / \mathrm{Re}^2 \tag{7}$$

Fig. 4(b) is the EHD number characteristic of the HPC when the fluid velocity is 1 m/s. It shows that the $N_{\mathrm{EHD}} > 1$ when the voltage is higher than 32 kV.

Fig. 5 are the potential and the space charge distributions of the collector when the applied voltage is 32 kV. Fig. 5(c) and (d) are the distribution at the half height position of the Z direction. The lines are the electric force line. It is showed that the current reaches the bag by though the holes of the perforated plate. Fig. 6 are the space charge density distributions of the perforated plate and the bag. The charges of both sides of the perforated plate moves toward the plate (Fig. 6(a), Fig. 6(b)). It is shown that the places against the wires have the highest charge density. And the charge density of the perforated plate is ten times that of the bag. Thus, the current reaches the bag is very small, just 0.13% of the total current, as the same as the Fig. 4(a) shown. Fig. 6(c) is the charge density distribution of the bag, containing 26 peaks. Each peak is corresponding to a hole of the perforated plate. Thus the perforated plate is a good protection for the bag, which would be damaged when the surface electric field is too strong.

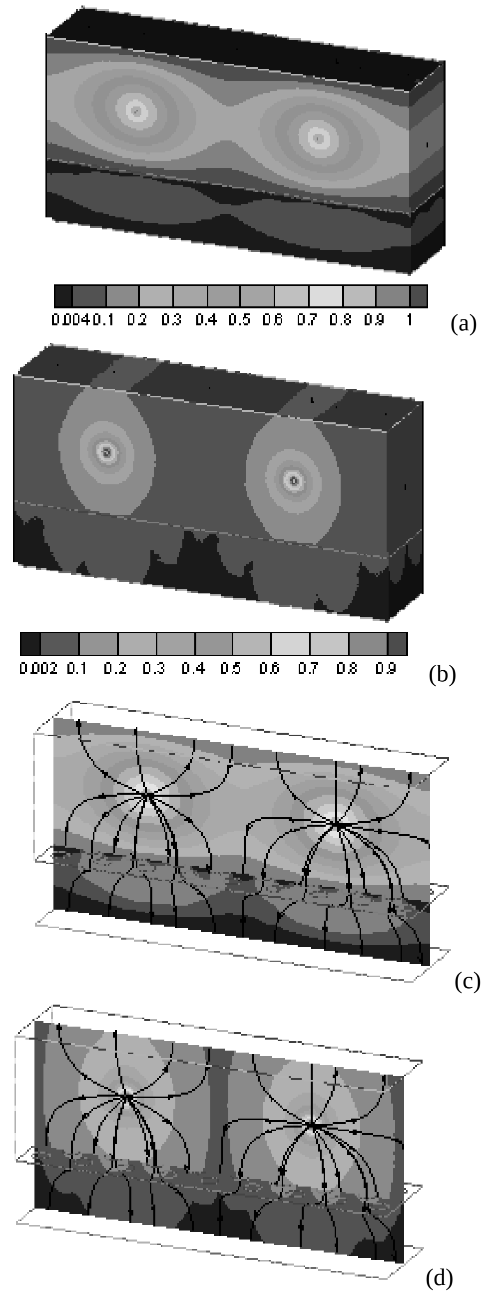


Fig. 5 The normalized distribution of the potential: (a,c) and the space charge density (b, d)

3.2 EHD Flow

The flue gas velocity in the industrial ESPs is about 1 m/s. Three inlet velocities were selected to research the EHD characteristics of the HPC: 0.1 m/s, 1 m/s, 2 m/s, of which the N_{EHD} equal 100, 1, 0.25, respectively.

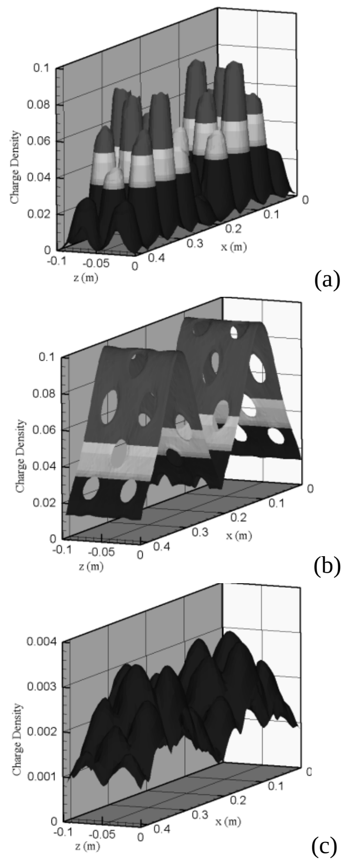
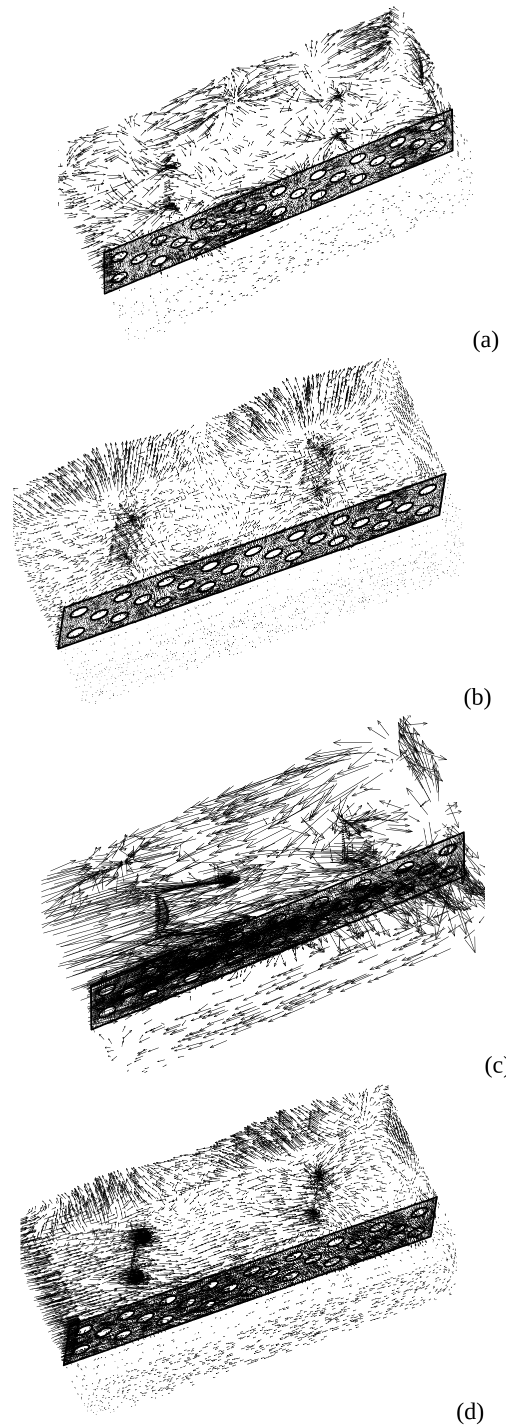
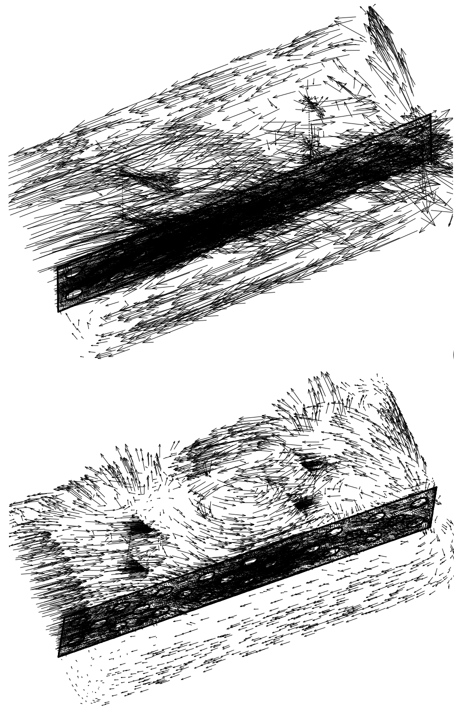


Fig. 6 The normalized space charge density: (a, b) perforated plate; (c) bag

Fig. 7 are the velocity vectors of the three cases. For each case, the left one is the results with no electric field, and the right one is the results with the electric field. With no electric field, when the inlet velocity is 0.1 m/s, there is just a little gas that flow back along the upper collection plate, but when the velocity is 1 m/s or 2 m/s, a lot of gas flow back along the collection plate, forming a big swirl near the second discharge wire. Besides, near the bag, the gases have the same behavior for three cases, but the inlet velocity higher, the gas velocity near the bag is higher too. With the electric field, for all three cases, the gases are driven to the collection plate, and the gas velocity near the bag slow down. This is because that the electric field near the upper collection plate is stronger than near the perforated plate. And it shows that the gas flows with the electric field contain more swirls, especially near the discharge wires. For the inlet velocity 2 m/s, an obvious swirl is formed between the wires. The electric field influences the gas flow a lot, even the inlet velocity is 2 m/s, of which the N_{EHD} equals 0.25. Thus, the EHD characteristics of the HPC are a little different from that of the ESP, for which the EHD influences little when the N_{EHD} lower than 1.

Figure 8 are the y direction velocity distributions of the three cases on the z = 0.048 plane. With no electric field, the positions of the maximum y direction velocity are all at the place about x= 0.4 m, and the velocity values are about 0.1 m/.s for inlet velocity 0.1 m/s, 0.2 m/s for the other two cases. But with the electric field, the maximum positions are changed to the places beside the upper collection plate against the discharge wires, and the velocity values are about 0.5 m/s. It also shows that the electric field has strong influence on the gas flow in the HPC, even the inlet velocity is 2 m/s.

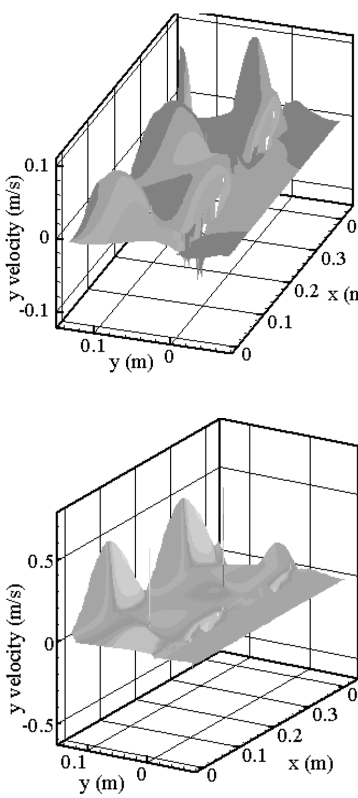




(e)

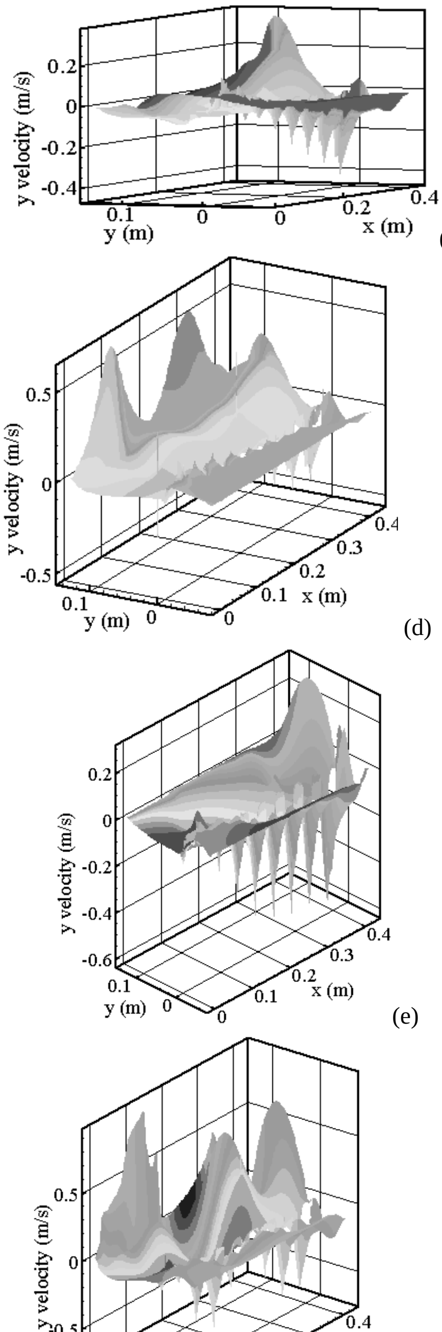
(f)

Fig. 7 The velocity vectors of the EHD flows:
(a, b) 0.1 m/s; (c, d) 1 m/s; (e, f) 2 m/s



(a)

(b)



(c)

(d)

(e)

(f)

Fig. 8 The velocity distributions on the z = -0.048 m plane: (a, b) 0.1 m/s; (c, d) 1 m/s; (e, f) 2 m/s

4 CONCLUSIONS

The EHD characteristics of an HPC were presented in this paper. The HPC is a good hybrid collector to capture the fine particles. It have big advantages in the collector cleaning. As the HPC contains the perforated plate, its electric field is more un-uniform than the ordinary ESP. The perforated plate has good protection for the bag filter. The current reaches the bag is just 0.13% of the total current. The electric field pushes the gas flow to the plate, and makes the gas flow contain more swirls than the case with no electric field in the HPC. Different from the ESP, the electric field has still strong influent on the gas flow when the $N_{EHD} < 1$.

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