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Electrohydrodynamic flows in electrostatic precipitator of five shaped collecting electrodes

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ABSTRACT

The electrohydrodynamic (EHD) flows in wire-plate electrostatic precipitators (ESP) of five shaped collecting electrodes are simulated by employing the CFD code FLUENT with the aid of a user defined function (UDF). The results show that the EHD flow patterns are different in the five configurations. Bending of the collecting plate can easily lead to the peak of the electric field intensity near the collecting surface. The space charge density near the W-type collecting surface is more uniform than those of the other four types. The flow induced by ionic wind in the C-type plate is strongest among the five channels.

1. Introduction

Environmental protection, especially air pollution control, has become a crucial problem of public concern in China, because energy consumption as well as the emission of environmental pollutants has grown dramatically with rapid economic development [1–4]. As one of the effective and reliable particulate control devices, the electrostatic precipitator (ESP) has been widely used for industrial gas cleaning with high dust removal efficiency. In the ESP channel, the electrode configuration and arrangement, producing the electrical characteristics and the features of the electrohydrodynamic (EHD) flow in the channel, are the most essential and important factors influencing particle collection efficiency. When corona discharge takes place in the EPS, the fluid flow interaction occurs between the primary flow and the secondary flow (sometimes also referred to as corona wind, electric wind, or ionic wind) caused by the high-speed electrical ions, which leads to a complicated turbulent flow, i.e., the EHD flow, and therefore influences the dynamic behavior of the charged particles.

Numerous experimental and numerical studies have been carried out on the electrical characteristics and EHD flow in the ESP over the past few decades. In fact, it is difficult to exactly measure both the flow field and the electrical field in the channel, by either direct or indirect testing, when the ESP is operating [5]. On the one hand, direct measuring techniques using probes, such as hot-wire probes, distort not only the electric field, but also the gas flow pattern. On the other hand, most non-intrusive optical techniques, e.g., LDV (Laser Doppler Velocimeter) and PIV (Particle Image Velocimeter), depend on what kind of tracer particle is used for the test, and the transportation of particles is not solely influenced by the flow field, but by the electric field also. Moreover, the space charge distribution in the channel can be changed by the charged tracer particle. Therefore, numerical analysis has been widely used to calculate the electric field, EHD flow and particle collection in ESPs since the 1970s. For example, McDonald et al. [6] numerically predicted the electric field by the finite difference method in the wire-plate ESP. The interaction of the electric wind and the inlet velocity in wire-plate precipitators was theoretically and experimentally investigated by Yamamoto et al. [7,8], who demonstrated that the electric wind induced flow was suppressed by the inlet flow. Angnostopoulos and Bergeles [9] present the electrical characteristics and flow features of a single electrode in the wire-plate ESP by the finite volume method. Kallio and Stock [10,11] analyzed the characteristics of uneven anisotropic turbulence caused by primary flow and secondary flow, numerically solved the electric field by a combination of the finite volume method and the finite difference method, and simulated the turbulent EHD flow in the wire-plate ESP by the standard k-ε turbulence model. More details of previous studies on this subject have been reviewed by Adamiak [12], Feng [13] and Arif [14] et al.

However, most of the above studies are limited to simple geometry of flat-plate-type collecting electrodes, only a few studies about EHD flow in ESP composed of shaped plates have been addressed. For instance, Lami et al. [15] numerically studied the electrical characteristics of C-type collecting electrodes by using the finite difference method. Bernstein et al. [16,17] analyzed the influences of the state-of-art electrode and Wavy electrode on the electrical characteristics and flow features without considering the effect of space charge on the electric field. Park et al. [18,19] studied the EHD flow characteristics in

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a model ESP of simple geometry composed of a single wire with a cavity by experiments and numerical calculations. Fujishima et al. [20] conducted a simulation to understand the EHD flow in a typical industrial ESP geometry, i.e. the spiked-type discharge electrode and convex-concave-type collecting plate. The results show that the concave zone of collecting electrode is beneficial to particle capture because the flow in the concave zone is relatively stagnant, and the convex zone does not influence the primary flow. Neimarlija et al. [21] used the finite volume method to investigate the characteristics of electric and flow fields in the C-type plate ESP.

Although previous studies have resulted in better understanding of the coupling flow in the ESP, few of them could exactly model the EHD flow phenomena in the channel with different shapes of collecting plates. It is difficult to comprehensively evaluate the characteristics of electric field, gas flow and particle capture in real ESP channels based on existing results.

In the present study, computational fluid dynamic (CFD) techniques are employed to simulate the flow characteristics in ESP channels with the influences of ionic wind. Five geometrical configurations of collecting electrodes are considered for the simulations. The finite volume method is used to solve the governing equations for determining the electric fields and space charge densities in the channel. The RNG k-ε model (Renormalization-group k-ε model) of EHD turbulent flow including electrical body force due to ion flow was used to evaluate gas velocity distribution.

2. Geometrical configuration of collecting electrode

The ESP channel consists of two collecting plates (collecting electrodes) through which the dust-laden gas is passed, and a series of equidistant wires (discharge electrodes) are placed in the middle plane between the two plates. Five shapes of collecting electrodes, shown in Fig. 1, are chosen to investigate the flow characteristics in the ESP channel when secondary flow caused by ionic wind exists.

The main parameters used for the numerical simulations are summarized in Table 1 [16,21–24]. Where S_x is the wire-to-wire distance, S_y is the wire-to-plate distance, a is the distance of two neighboring collecting rods/tubes (Fig. 1(b)), b is the half-height of the W-type cavity (or called zigzag type, Fig. 1(c)), c is the height of the C-type cavity (Fig. 1(d)), d is the edge length of the angle (Fig. 1(e)), r is the radius of the discharge wire, k_{ion} is the ion mobility coefficient, D_e is the ion diffusivity coefficient, U_0 is the applied electric potential at the discharge electrode, J_t is the average current density on the collecting electrode, i/l is the specific current.

For the sake of simplicity, cylindrical wire is considered as the discharge electrode. In much previous work for modeling the EHD flow in wire-plate ESPs, the geometry of the channel was usually simplified to a single wire configuration [17–19]. Because a single wire model might not capture properly the flow and particle collecting behaviors in a real ESP channel, multi-wire configurations have been taken into consideration in the past two decades [13]. Therefore, three discharge electrodes are used to investigate the effect of inlet and outlet on the flow as well as avoid the distortion of numerical results. The EHD turbulent flow in the channel is assumed to be fully developed isotropic turbulence with normal temperature. Due to the symmetry of the channel, the computational domain is reduced to only the upper half of the electrostatic precipitator channel between the collecting electrodes and discharge electrodes, as shown in Fig. 1.

3. Numerical model

3.1. Governing equations

The EHD turbulent flow is governed by the time-averaged continuity and Navier-Stokes equations including a turbulence model and the influence of electrostatic force. For the geometrical configurations of the electrode systems shown in Fig. 1, the flows in the channels can be treated as two-dimensional, steady-state and incompressible, and the governing equations take the forms [7–12]:

Conservation of mass

$$\frac{\partial u_k}{\partial x_k} = 0 \tag{1}$$

Conservation of momentum

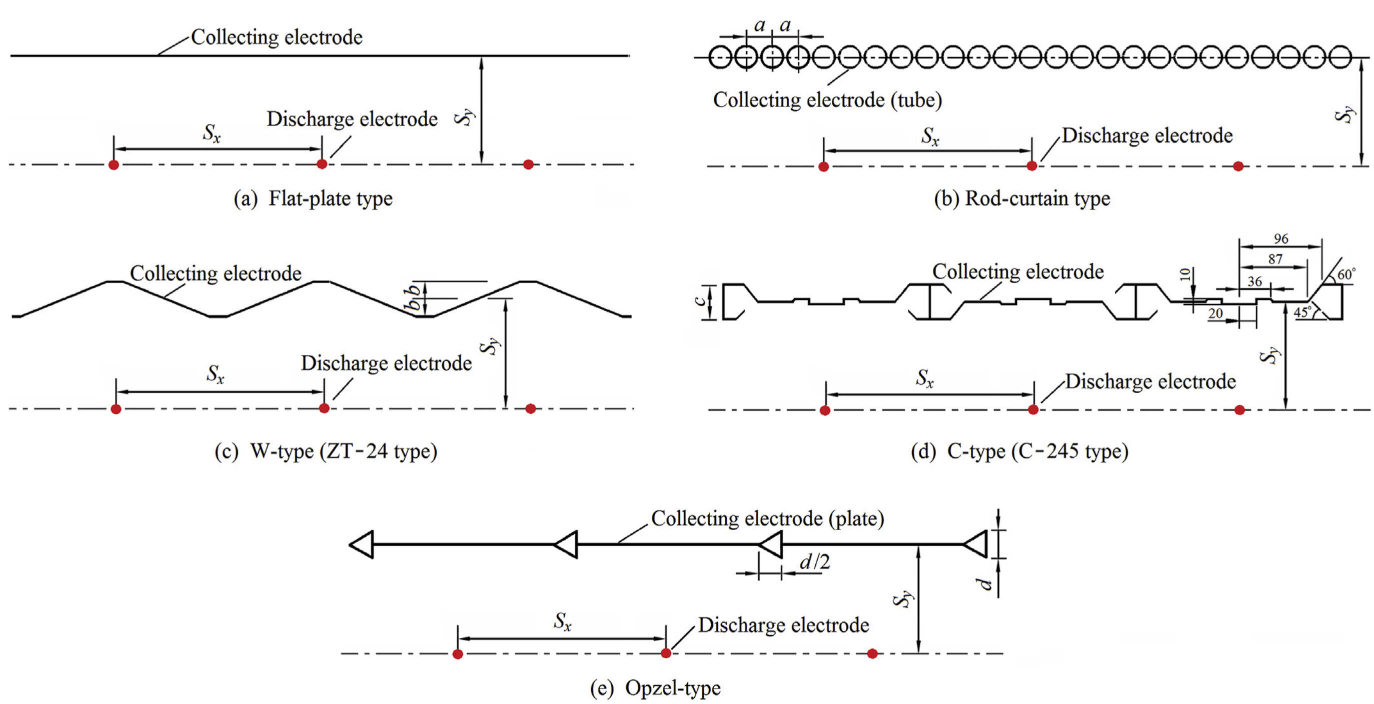

Fig. 1. Geometrical configurations of the ESP channel with five shaped collecting electrode systems (dimensions in mm).