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Simulation of the electric field in wire-plate type electrostatic precipitators

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ABSTRACT

The paper presents a general Control Volume model for electric field simulation in wire-plate type electrostatic precipitators, along with a new injection law for charge density. The model is validated against empirical equations and experimental data in the literature when applied to the wire-plate and point-plate configurations. The voltage current characteristics and detailed distribution of field and charge density are characterized, particularly for the case of barbed wire electrode. The effects of geometric variations, such as the sharpness of the tip and the direction of the needles with respect to the plate, are investigated.

1. Introduction

Electrostatic precipitation has been used in chemical processing, power generation and mass transport applications. The most common geometry for electrostatic precipitators (ESP) is the wire-plate type. The numerical simulation of detailed electric field is essential for the study of electro-hydrodynamic gas flow and collection efficiency for dust particles.

The major phenomena involved and numerical treatments in the previous computational studies are outlined below. The glow corona discharge is confined in a small, bright region near the high-voltage electrode (ionization region), where ionization processes can occur in the form of electron avalanches [1]. The ions produced in the ionization region drift outside towards the plate electrodes (drift region). Attempts have been made to determine the so-called corona sheath radius [2], so the simplest way is to shift the inner boundary conditions at ionization radius r_i rather than at the wire radius r [3–5].

$$r_i = r + 0.03\sqrt{r}$$

However, in real situations the corona sheath radius increases as higher voltage is applied. Moreover, this treatment is limited to the circular wire electrode with constant radius. Uncertainty arises when determining the artificial boundary for general 3D configuration and discharge electrode of any shape, where the radius of curvature varies from point to point. The ionization region is typically narrow, and practically can be neglected for its complex physical processes. Therefore, the boundary condition can be specified directly on the electrode surface. The threshold of the electric field can be calculated by Peek's law [6]. The surface charge density is determined either iteratively according to the Kaptzov hypothesis [7], or by using a simple inception law in the form of [9]:

$$\rho = a(E - E_0)$$

Kim et al. [8] suggested $\rho = a(E - E_0)^\alpha$ with the exponent ranging from 1.5 to 2.2 for the wire electrode. A key issue remaining would be to sufficiently resolve the high gradient at the sharp electrode and to sensibly specify the boundary conditions, so that the above simplification does not impact on the overall model accuracy. For an axisymmetric needle of hyperbolic shape, Atten et al. [9] used a hyperboloidal coordinate to transform the domain of integration into rectangular, which facilitates the finite differences. For general 3D cases, various numerical techniques (Method of Characteristics, Finite Element method, Boundary Element method, Finite Volume method, or their combination) were used and special attention was paid to numerical issues, such as the order of discretization scheme, shape and resolution of the mesh elements [10,11]. Accurate computer simulation of such

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a general 3D corona proved to be more difficult than it appears [12].

There have been a large number of studies on the wire-plate type (see, for example, [13–16]). However, electrode configuration characterized by a sharp discharge electrode is still a challenge [17]. In particular, barbed wire electrodes are widely used, where many sharpened spikes are attached to a frame wire to enhance corona production. The electric field in this case is fully three-dimensional, with combined features of wire and point electrodes. This configuration has advantage over its precessors for stable corona over a wide range of operation conditions. Relatively fewer numerical studies have been reported to focus on the barbed wire corona with any configuration [10,11]. Quantitative characterization of the electric field and optimization of the design are practically significant. Particularly it will be useful for accurate analysis of the electro-aerodynamic flows [18–20] and subsequently the fine particle transport behaviours [21,22].

Although different methods have been used for different configurations, a robust universal model is lacking at present, but should be more useful for engineering applications. The current paper uses a finite volume method based on commercial software, ANSYS-CFX [23], to achieve this goal. In particular, it is focused on barbed wire-plate type ESP, which is widely used in practice.

2. Numerical method

The distributions of the electric potential and space charge density are controlled by a Poisson equation and current continuity equation, respectively, given by

$$\nabla^2 V = -\rho \Big/ \varepsilon \tag{1}$$

$$\nabla \cdot J = 0 \tag{2}$$

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

$$\mathbf{J} = \rho(b\mathbf{E} + \mathbf{U}) - D\nabla\rho \tag{4}$$

The ionic diffusion coefficient D is related to the ion mobility b, given by

$$D = \frac{bk_{\mathrm{B}}T}{e} \tag{5}$$

Note that the diffusion term is normally much smaller than the advection term, thus can be safely overlooked. In addition, the Peek equation is used to determine the corona onset threshold on the discharge electrode (with unpolluted smooth surface),

$$E_0 = 3.1 \times 10^6 [V/m]\delta\left(1 + \frac{0.0308\left[m^{0.5}\right]}{\sqrt{\delta r}}\right) \tag{6}$$

However, the following form of the Peek formula is considered to be more accurate in the present study [11],

$$E_0 = 2.72 \times 10^6 [V/m]\delta\left(1 + \frac{0.054\left[m^{0.5}\right]}{\sqrt{\delta r}}\right) \tag{7}$$

where r is the radius for cylinder and half the radius of sphere. For an arbitrary surface, r is the local radius of curvature, calculated from the two principal (maximum and minimum) radii of curvature at the point concerned,

$$\frac{1}{r} = \frac{1}{r_1} + \frac{1}{r_2} \tag{8}$$

The corona model is simplified by neglecting the ionisation layer, and considering only one ionic species, moving with a constant mobility. It must be emphasized that the Peek equation above will be used whether or not the electric field is the same at all the points of the corona electrode. The crucial issue concerns the boundary conditions for the space charge density on the corona electrode. In the current study, we explicitly implement boundary condition on the exact surface of the discharge electrode, combined with an injection law:

$$\begin{cases} \rho = 0 & E \le E_0 \\ \rho = ab\varepsilon E_0(E - E_0) & E > E_0 \end{cases} \tag{9}$$

where $a = 0.05\ \mathrm{s\ m^{-2}}$ is an empirical constant. Note when a is very large, the injection law would lead to the Kaptzov condition, thereby the field strength remains constant at Peek's onset value at every coronating point (refer to discussion in [9]). However, the Kaptzov's assumption, which has been applied in majority of the previous studies, leads to some deviations with increasing voltage. As can be seen, we introduce several parameters to elaborate the injection law. As will be demonstrated, the delicate injection law can overcome the above deficiency to a certain extent. A possible reason is that the field strength on the injecting surface can exceed the onset threshold, thus able to compensate for model error caused by the neglected ionisation region. As a result, this method, if not universal, should be extended in its general applicability.

Commercial software ANSYS-CFX Release 14.0, a finite volume based flow solver, along with user defined subroutines, is used for the solution of the coupled conservation equations. The computational mesh consists of mixed elements of different shapes, including hexahedra, tetrahedral, prisms and pyramid. Generally, due to the sharp electrode, gradual local mesh refinement is required to resolve the large gradients of the potential and charge density near the corona electrode surface. An example of the mesh patterns, with close-up displays, is given in Fig. 1. The control volume is constructed around a mesh node, using barycentric tessellation. The variables are stored on the mesh node and interpolated to the integration points on the control volume faces via a tri-linear shape function. An Electric Potential module is available in the code, where the user can specify the space charge density as the source term. The ion charge density is solved via a standard advection-diffusion transport equation of a user scalar, where the advection velocity takes the ion drift velocity. Discharge electrode is set as the inlet of the charge, while the plate is the outlet. A high resolution scheme is chosen for the advection terms of the charge density, which is a second order upwind scheme but bounded for better stability.

The set of coupled equations, together with the injection law, are solved iteratively until converged. During the solution, the field strength, E, in the injection law takes its value from the previous iteration. The result is considered to be converged only if three criteria are met simultaneously: (1), all the field variables and the global quantities (e.g. the total current, mean field strength on the plate) do not change with further iterations; (2), the current and the electric displacement are globally balanced with relative error below 1%; and (3), the residuals of the conservation equations are substantially reduced to the order of 10^{-5} relative to the global flux. Convergence can be enhanced or speeded by double precision numeric, strong under-relaxation for the boundary charge density. These factors, however, have no bearing on the final result. It should be pointed out that, in the converged result, the injection law is always enforced, so that the field strength over the coronating part of the surface satisfies $E > E_0$.