PARTICLE TRAJECTORIES IN A PLATE – PLATE ELECTROSTATIC PRECIPITATOR WITH HORIZONTAL IONIZING BLADES

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ABSTRACT

The trajectories of fine particles (≤ a few μm) in an electrostatic precipitator (ESP) are modelled taking into account the secondary gas flow induced by horizontal ionizing electrodes. In particular, in an electrostatic precipitator with horizontal ionizing blades, the secondary flow in the form of axial rolls can be vigorous and the resultant gas flow inside the precipitator can be considered as axially invariant to a first approximation. A numerical simulation of charging, transport and collection of fine particles is presented, based on the approximation of a gas flow independent of the axial variable. The bi-dimensional character of the distributions of electric field E and ionic space charge q which plays an important role in the charging of particles is taken into account. This allows simulating the particles trajectories and the dynamics of their charging.

1. INTRODUCTION

Electrostatic precipitation is a commonly used technique to clean the gases exhausted in atmosphere by many industrial factories or plants. But the efficiency of collection of industrial precipitators (ESPs) is generally poor for the fine particles of size ranging from 0.1 to 1 μm which are hazardous for human health. In order to try to improve the removal of fine particles it is necessary to characterize their properties and behavior during the precipitation process. Many attempts were proposed to account for the observations and measurements on laboratory and industrial ESPs. The oldest one is the simple analytical approach of Deutsch [1] refined by Leonard [2]. More recently numerical models were developed by several authors (Meroth [3], Medlin [4], Egli et al. [5], etc..). The electrohydrodynamic effects are retained with different degrees of complexity. However, almost all recent numerical models consider the simplified case of homogeneous discharges along the cylindrical corona electrodes, which restricts the influence of the electrical forces on the gas flow mainly to velocity modulation in a horizontal plane (*Oxy* in Fig. 1-a).

In a previous work performed on two laboratory ESPs with vertical “barbed” electrodes and horizontal ionizing blades [6,7,8], a rather vigorous secondary flow in the form of axial rolls was observed as sketched in Fig. 1-a. These rolls arise from the periodicity along the vertical direction *Oz* of the distributions of electric field $\boldsymbol{E}$, charge density ρ and force density $\rho\boldsymbol{E}$. A first important observation is that the gas flow inside the filter exhibits the same structure in all cross-sections *Oyz*. To a first approximation, the secondary flow does not depend on the axial direction *Ox*. This two-dimensional (2-D) character of the large scale secondary gas flow allowed to perform a rather simple analysis of particle motion in a convective cell (Fig. 1-b).

2. TWO-DIMENSIONAL (2-D) NUMERICAL MODEL OF GAS FLOW

We retain the case of the plate-plate electrostatic precipitator with horizontal ionizing blade (Fig. 1a). The flow visualization [6-9] reveals a well organised secondary flow with rather strong velocity components in the *Oyz* plane. The gas motion is vigourous and must

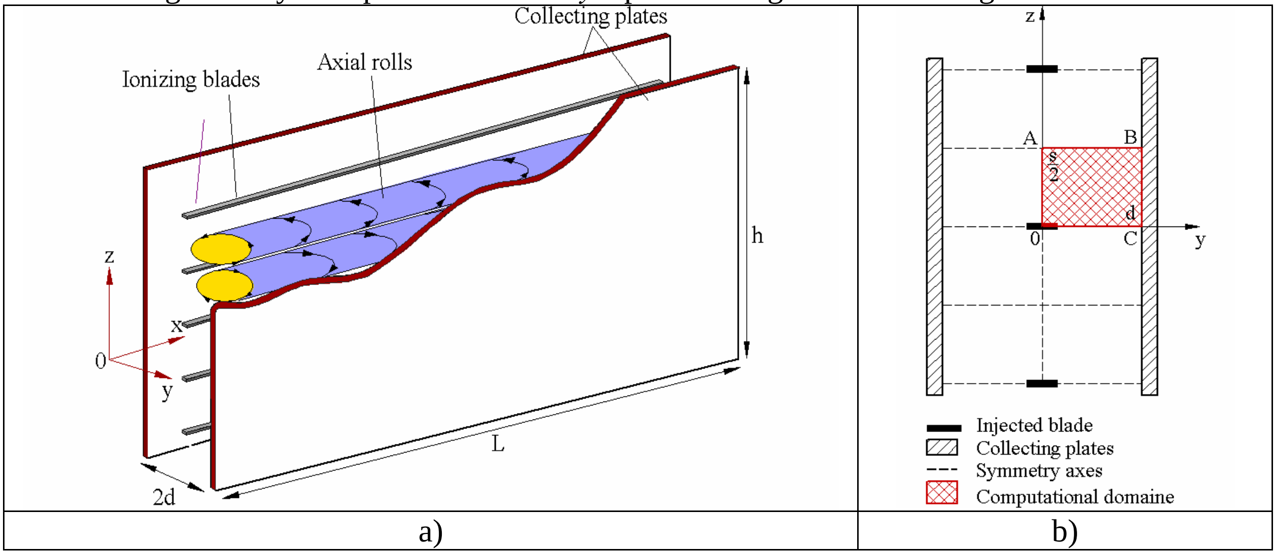

Fig. 1. a) Plate – plate with ionizing blades investigated precipitator with schematic axial rolls; **b)** Convective cell (computation domain).

have some marked effect on the particule trajectories and on their collection. To go further in this study and get a better estimation of the influence of gas flow structure, we do perform a numerical study concerning the charging process and trajectories of the particles inside of a convective cell (Fig. 1b).

The determination of the solution of the gas flow problem is difficult due to the 3-D character of the Coulomb force density distribution and of the associated flow. Nevertheless, as the mean cross flow pattern appears to be approximately invariant along *Ox*, it is not unrealistic to consider a much simpler 2-D problem. Indeed the forced gas flow, which tends to damp out the secondary rolls of vertical axis does not strongly affect horizontal rolls (the mean streamlines are then helices). The problem can be simplified by considering that the 2-D force density resulting from averaging F_e (electric strenght acting on the gas) along the Ox direction drives the axial rolls. We can then formally accept an uniform injection of charge along of horizontal blades (which permit to consider a plane symmetry of ionic space charge and electric field).

The problem is governed by the equations of Poisson, Navier-Stokes and conservation of current and mass:

$$\nabla^2 V = -\frac{q}{\varepsilon_o} \tag{1}$$

$$\frac{\partial q}{\partial t} + \nabla \mathrm{j} = 0 \tag{2}$$

$$\nabla\ \mathrm{U} = 0 \tag{3}$$

$$\rho_g\left(\frac{\partial \mathrm{U}}{\partial t} + \mathrm{U}\nabla\ \mathrm{U}\right) = -\nabla p + \eta\nabla^2 \mathrm{U} + q\mathrm{E}\ , \tag{4}$$

where V and $\boldsymbol{E} = -\nabla V$ are the electric potential and field, q is the charge density, ε_0 the gas permittivity, $\boldsymbol{j}$ the current density, $\boldsymbol{U}(u,v,w)$ the gas velocity field, ρ_g the gas mass density, p the pressure and η the gas dynamic viscosity.

The constitutive equation for the current density is:

$$\boldsymbol{j} = q\left(K_i \boldsymbol{E} + \boldsymbol{U}\right) - D\nabla q \qquad (5)$$

where K_i and D are the ion mobility and diffusion constant respectively.

The diffusion current is totally negligible in comparison to the current due to the drift of the ions. Since the drift velocity of ions (~ 60 m/s) is much higher than the typical velocity U_g of the forced flow, the convective component is neglected in the ionic current density, which is simply:

$$\boldsymbol{j} = K_i\, q\boldsymbol{E}. \qquad (6)$$

Therefore the "electrical" problem can be decoupled from the "hydrodynamic" one. At steady state, equation (2) leads to:

$$\boldsymbol{E}.\nabla q + \frac{q^2}{\varepsilon_o} = 0 \qquad (7)$$

The assumption of a 2-D problem (the x derivatives of all variables except the pressure is zero) results in a decoupling of the two equations for the components v and w of the velocity vector [9,10]. Classically a stream function Ψ is introduced defined by [9,10] :

$$v = \frac{\partial \Psi}{\partial z}, \qquad w = -\frac{\partial \Psi}{\partial y} \qquad (8)$$

Denoting the axial vorticity by Ω, eq. (4) leads to :

$$\nabla^2 \psi = -\Omega \qquad (9)$$

$$\rho\left[\frac{\partial \Omega}{\partial t} + \frac{\partial \Psi}{\partial z}\frac{\partial \Omega}{\partial y} - \frac{\partial \Psi}{\partial y}\frac{\partial \Omega}{\partial z}\right] = \eta \nabla^2 \Omega - \frac{\partial V}{\partial z}\frac{\partial q}{\partial y} + \frac{\partial V}{\partial y}\frac{\partial q}{\partial z}\,. \qquad (10)$$

The component of the gas velocity in the Ox direction u results from Navier-Stokes equation on this direction (remembering that $\frac{\partial u}{\partial x} = 0$):

$$\frac{\partial \boldsymbol{u}}{\partial t} + v\cdot\frac{\partial \boldsymbol{u}}{\partial y} + w\cdot\frac{\partial \boldsymbol{u}}{\partial z} = \frac{1}{\rho_p}\cdot\left(-\frac{\partial p}{\partial x} + \eta_g \cdot \Delta \boldsymbol{u}\right) \qquad (11)$$

By taking into account the periodicities and the symmetries, the computing domain is restricted to the section of one roll, y varying from 0 (the center of the blade) to the collecting plate and z from 0 to $s/2$ (s is the vertical period of the blades) represents the calculus cell. The details concerning the boundary conditions of constitutive equation can be found in [9,10,11].

The equations have been put in finite differences form using a rectangular mesh. The Poisson equation is solved using the successive over-relaxation method (SOR). q is obtained by using the method of characteristics. The solution of the electrical problem is determined by successive approximations: V being given, a new q distribution is obtained by interpolating between the previous one and the solution of (7); then a new V distribution is determined by

solving (1). The computation starts by taking the harmonic potential. About 10 successive approximations are usually enough to achieve a good convergence [9,11].
The vorticity equation, (10) defines an initial-value problem treated by using the first upwind differencing method [9-11]. Once the vorticity distribution is obtained, we do solve the equation (9). The calculation (resolution of (9) and (10) alternatively) is continued up to a point where a steady state is reached. The equation (11) is similar with (10) and we do solve it using the same method. Here the source term is the pressure gradient and we choose a value which led to a mean gas flow velocity in the x direction of ~1 to 2 m/s.

3. PARTICLE TRAJECTORIES MODEL

Based on the determined distributions of electric field, ionic charge space density and velocity field of the gas flow, we developed an exploratory study on the trajectories of particles inside of a convective cell. We focus our study on fine particles trajectories (particles diameter d_p~0.1 to 3 µm) and do neglect some of the smallest strength acting on the particles (gravitationnal strengh, Magnus effect and Basset strength…[12]). Then on the basis of the fundamental relation of dynamics the trajectory of a particle is defined by the following equation:

$$\frac{d\vec{r}}{dt} = \vec{U}(x,y,z) + Cu(d_p)\frac{\varepsilon_r}{\varepsilon_r + 2}\sqrt{\frac{\rho_g}{\varepsilon_0}}\frac{\gamma_g}{V_{appl}} \cdot q_p \cdot \vec{E}(x,y,z) \qquad (12)$$

where $\boldsymbol{r}$ is the position of particle, q_p is the particle charge, taking as reference the saturation charge q_{lim} , evaluated using (13) for a mean electric field V_{appl}/d and ε_r is dielectric constant of the particle material. Cu(d_p) is the Cunningham factor that have to be used in the Stokes law when the particles size is not too large in comparison with the mean free path of gas molecules (λ_g =0.065 µm for air).

The saturation charge is expressed as follow [13]:

$$q_{\lim}(d_p) = \pi\varepsilon_0\beta \cdot d_p^{\ 2} \cdot \mathrm{E}(x,y,z) \qquad (13)$$

The charge q_p is a function of time and we retained the so-called “Field-Modified diffusion“ charging model developed by Lawless [14,15]. This model retains the two basic mechanisms of field (q_f) and diffusion (q_d) charging. While the field charging process is dominant for particles diameter above 1µm, the diffusion charging process becomes predominant for particle diameter under this size. Nevertheles, both mechanisms participate to the accumulation of charge on particle until the saturation charge (q_{lim}) is reached. Then the only mechanism involved in particle charging is the diffusion charging process. The detalied equation of charging process are given in [14,15].

4. PARTICLE TRAJECTORIES AND CHARGE SIMULATION

In this model, the entry length corresponding to the development of the secondary flow is ignored. One of the most drastic approximations is to retain only the steady state vortical motion thus fully neglecting the effect of turbulence even though the mean velocities v and w depend globally to a certain degree on turbulence (the computations were performed with a mean velocity field corresponding to 1.3 m/s). We therefore obtain qualitative rather than quantitative results.

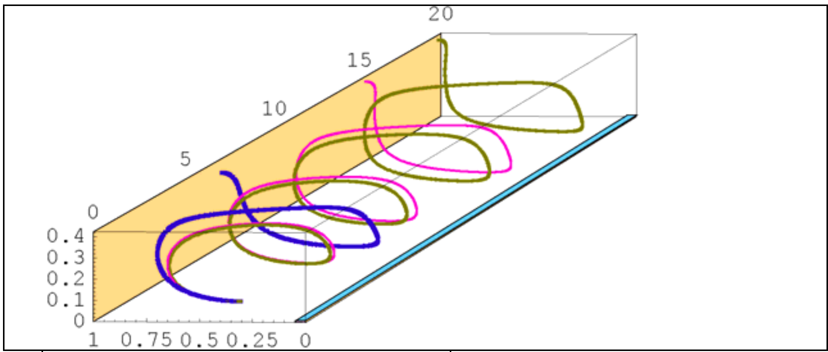

Fig. 2. Example of particle trajectory inside of a convectice cell for d_p = 0.5, 1 and 3 μm injected at the same entrenance point (V_{appl} = 20 kV, U_g = 1.3 m/s).

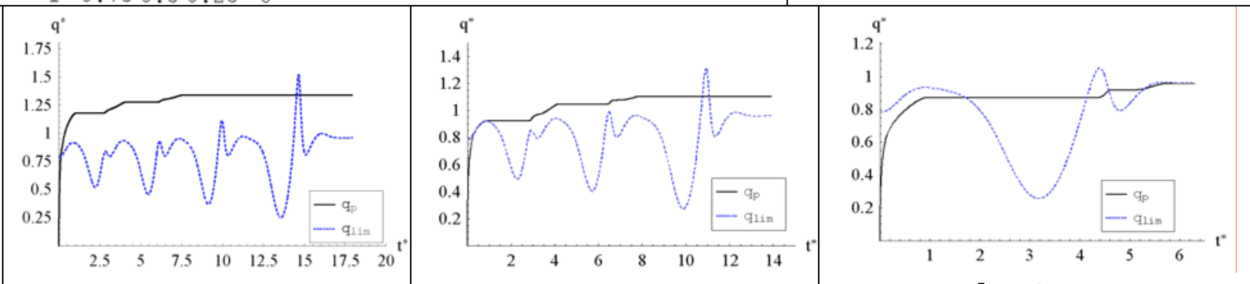

Fig. 3. Evolution of adimensional particle charge and charge limite along of the coresponding trajectorys given in Fig. 2

Fig. 2 shows an exemple of particle trajectories inside of a convective cell. We can see that the particle trajectory (practicaly the collection process) strong depends of the particle diameter d_p. An important factor which can explain that is the evolution of the particle charge inside of the filter (Fig.3). These three examples shows that the time evolution of the charge q_p of a particle depends on its trajectory (through the local values of the field and of the ionic space charge). It is clear that along the trajectory, at every position on the trajectory, the charging depends on local ionic charge density q and field strength. This leads to a steep increase in q_p when the particle passes from a region of low charge density and/or electric field to one with high values of q and E. Fig. 4 a) and b) shows the importance of the entrance point of the particle in the filter (at x = 0) and the influence of the gas flow structure. Because the flow structure, the trajectory and the collection process strongly depends "the start" of each particle. Fig. 4 c) and d) presents the influence of particle diameter on the collection distance and charging process. For this example, when the entrance point is located on the symmetry boundary (OC – Fig.1-b) of the convective cell, it is interesting to observe that, the small particle (d_p = 0.1 μm) can acquire a most important charge. In a first view, these results can appear stranger because the particle charge depends of their diameter. If we examine the Fig. 2 this observation is consistent because the small particles have the longer trajectories (several passages in the zones with high values of q and E) and, in consequence, the time of charge is different (see also Fig. 3).

5. CONCLUSION

The numerical study that has been presented in this paper illustrates the extend and trends of large flow distortion, in shape of longitudinal rolls, in laboratory scale duct precipitator using ionizing horizontal blades electrodes. One of the most essential results that have rising up is that the dynamic of particle strongly depends of the gas flow structure, spatial distribution of ionic charge and electric field and particle charge. These results however, are rather qualitative than quantitative. One shall keep in mind that, in our model, we did use assumptions that can have significant influences on the values obtained for the particle charge. To simulate the particle trajectories the modulation of the injection of charge (corona discharge) according to O*x* direction is neglected. Thus, this can have significant consequences on the charge q_p, the spatial distributions of the electric field and space charge density is not representative of the real one. Another simplification consists in neglecting small scale turbulence; this one influences the movement of the very fine particles (lower than 0.5 µm) .

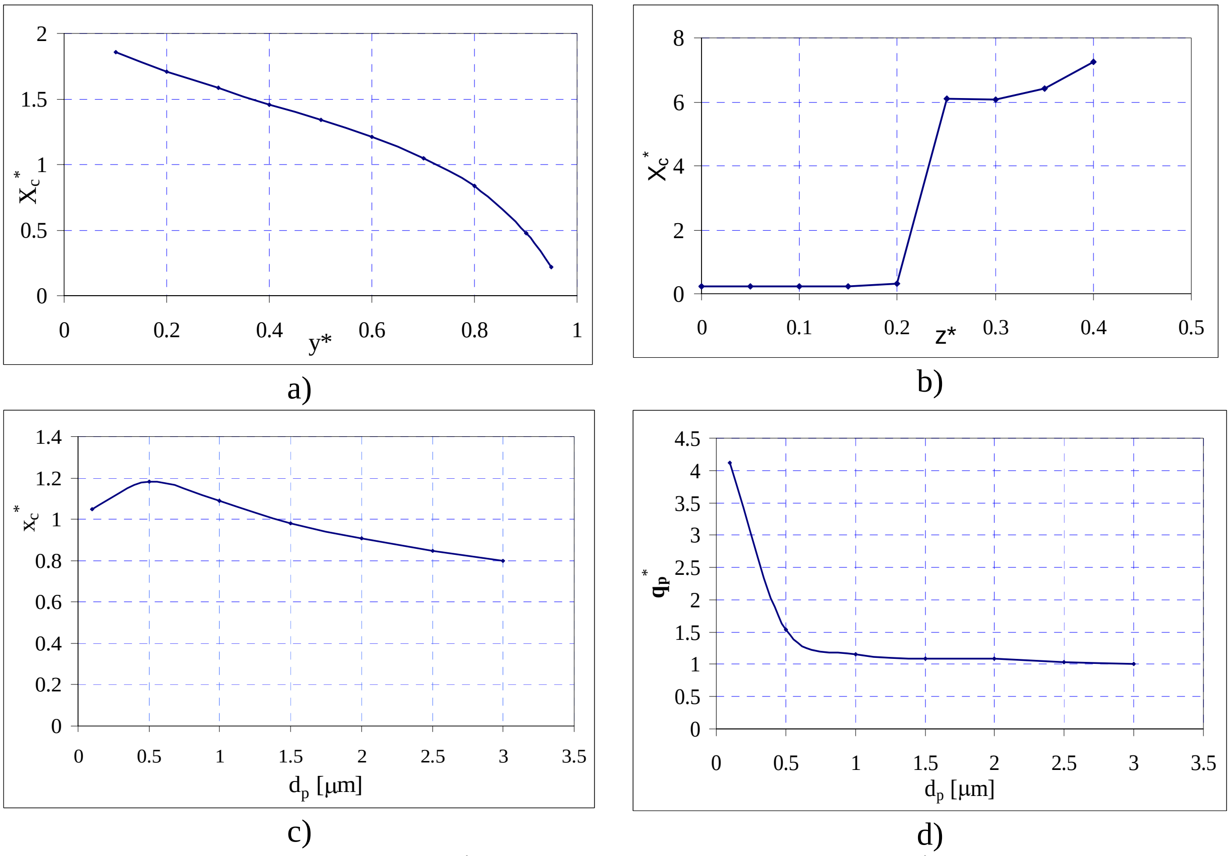

Fig. 4. a) Collection distance x_c^* as a function of entrance coordinate y^* for d_p = 0.1 µm; **b)** Collection distance x_c^* as a function of entrance coordinate z^* for d_p = 0.1 µm; **c)** Collection distance x_c^* as a function of particle diameter for the entrance point (0.7, 0); **d)** Particle charge as a function of diameter d_p for the entrenance point (0.7, 0).

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