Contribution to the Development and Technology of Electrostatic Precipitator

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***Abstract*— This paper deals with the numerical simulation of the particle's trajectory in an airflow under the room temperature and atmospheric pressure in the plane-plate configuration [1]. The research of the present paper is focused on time dependent studies of the precipitation process by visualizing the particle's trajectory towards the collecting electrode in ESPs. A set of coupled differential equations based on Maxwell's equations and the finite element method, are numerically computed using FEM solver software for their implementation and 3D distributions of electric potential, electric field, induced airflow velocity and particle motion are obtained in the planar plate system [2]. This model is proposed as a description of the electrostatic precipitation and can be used to study the influences of many factors on the particle's trajectory, including the applied voltage, dust loading and the fluid-flow velocity. The results of numerical predictions are reported and discussed.**

Keywords: Electrostatic Precipitator, Numerical Simulation, Charged Particle's Trajectory, Electric Potential, Laminar Flow, Migration Velocity, Electrostatics.

I. INTRODUCTION

Electrostatic precipitation is a technique to remove suspended small-scale dust particles in the gas stream using an electrostatic force that charges the dust particles and then attracts them toward the collecting plates.

Due to their high efficiency and low costs, electrostatic precipitators (ESP) are widely used in various industries and also have been applied for cleaning of indoor air in houses, offices and hospitals.

They play a major role in environmental protection, since the awareness of air pollution and environmental impact of the rejections by industry and transport has prompted legislators to set standards on air quality.

The researchers are using both experiments and numerical simulations to study and optimize the design of this system.

Knowing the behavior of charged particles in airflow is a crucial information to optimize precipitator efficiency which is influenced by a wide range of factors such as electrode geometry, particulate space charge, electrostatic field and diameter of particles.

The present study attempts to provide a more realistic prediction of gas and particle dynamics inside an ESP. The subject of this work is to simulate the electric field, the flow field and the particle motion under electrostatic and drag forces. These simulations are the first step towards the complete description of the conditions and processes in the ESP.

II. NUMERICAL METHODOLOGY & MODEL DEFINITION

The simulation described in this work is the first step towards a complete description of the physical and electrical processes in the ESP. The conditions in the ESP before operating are detailed.

A. Model Description

A 3D model can be assumed. The geometry modeling (see fig.1) consists of two large horizontal parallel conducting plates separated by inter-electrode space.

A positive DC voltage is supplied to the upper plate and the bottom one is to the ground. The gas between both electrodes is air at room temperature an atmospheric pressure. The airflow has an initial velocity at the inlet.

The dimension parameters are given below.

TABLE 1: PARAMETERS USED FOR SIMULATIONS

Name	Expression	Description
L	0.30 [m]	Length of the electrode
e	0.005 [m]	Thickness of the electrode
W	0.14 [m]	width of the electrode
H	0.08 [m]	Inter-electrode Space
V_{dc}	25 [kV]	DC applied voltage
V_{xo}	1 [m/s]	Initial Airflow velocity at the Inlet

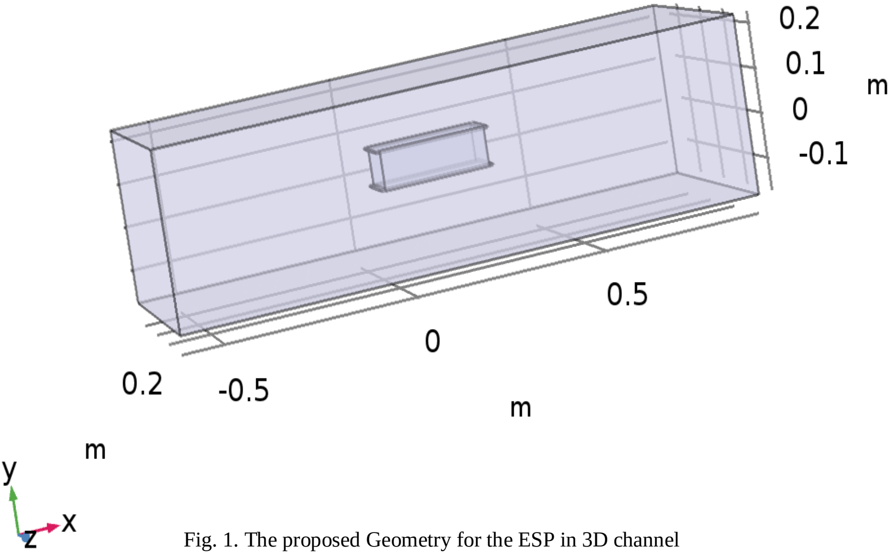

Fig. 1. The proposed Geometry for the ESP in 3D channel

B. Numerical Approach

es, ***spf*** and ***fpt*** modules were used for the simulations and have been tested and their suitability is discussed.

1. Governing Equations

The governing equations for the flow problem are the continuity and Navier-Stokes equation with an additional term take into account the effect of the electric field on the flow field. In addition, the effect of the particles on the electric and velocity fields is small, and a useful simplification is made by assuming one-way coupling, i.e., the electric field affects the particle motion, but not vice-versa. The unsteady governing equations for incompressible electro-hydrodynamic flows in three dimensional, including the electrostatic force as a source term, are given as [18]

1.1. Electrostatics module

Where the dependent variable is the electric potential: V.

Gauss's law [3,4]

$$\nabla \cdot D = \rho_v \tag{1}$$

E the electric field connected with the electric potential via the formula

$$E = -\nabla V \tag{2}$$

where: D −electric displacement (C/m^2), ρ_v −volume charge density (C/m^3), E −electric field intensity (V/m), V −electrostatic potential (V).

1.2. Fluid flow module

Where the dependent variables are:

-Velocity field : u and its components : $\begin{cases} u \\ v \\ w \end{cases}$

-Pressure: p

The gas flow motion is governed by the set of the Navier-Stokes equations together with the continuity equation for laminar incompressible flow [5]:

$$\rho \frac{\partial u}{\partial t} + (u \cdot \nabla) u = \nabla \cdot \left[-p + \mu \left(\nabla u + (\nabla u)^T \right) + F \right] \tag{3}$$

$$\rho \nabla \cdot (u) = 0 \tag{4}$$

where:ρ −air density (kg/m^3), u −air velocity (m/s), t −time (s), p −gas pressure (Pa), μ −air dynamic viscosity (Pa.s) and F −the body force acting on the gas (N).

1.3. Charged Particles' Motion module

Where the dependent variables are:

-Particle position: q and its components : $\begin{cases} q_x \\ q_y \\ q_z \end{cases}$

-Particle temperature: T_p

-Particle mass: m_p

In order to characterize the movement of charged particle in an ESP it is necessary to assume the equilibrium of forces acting on the particle. After some simplifications, it can be said that the following forces are acting on a dust particle in an ESP: the inertia force, electric force and drag force of the medium.

The motion of any dust particle may be described as by the Newton second law [6]:

$$\frac{d\left(m_p v\right)}{dt} = F_t \tag{5}$$

TABLE 2: CHARACTERIZATION OF PARTICLES

Name	Portland Cement Powder
Physical Properties *Particle size (Equivalent Diameter) (µm) *Density (kg/m^3)	128 1600
Electrical Properties *Dielectric constant *Resistivity (Ω.m)	2.6

- ❖ Electrostatic Force

When the charged particle passing a charge, Qs is in a region where an electric field strength of Ec is present, a force Fe will act on particle [6].

$$F_e = Q_s E_C \tag{6}$$

- ❖ Drag Force

The migration of particle towards the collector is resisted by a drag force and the net force on the particle is zero when it moves with a constant drift velocity [6].

$$F_D = \frac{1}{\tau_p} m_p \left(u - v\right) \tag{7}$$

Particle relaxation time or time constant

Characterizes the time required for a particle to adjust or "relax" its velocity to a new condition of forces and is not affected by the external forces acting on the particle.

$$\tau_p = \frac{\rho_p d_p^2}{18\mu} \tag{8}$$

Here, we denote: μ –viscosity of the gas (Pa.s),

- The saturation charge on a spherical particle is determined by the formula [6]:

$$Q_s = \pi\varepsilon_0 \frac{3\varepsilon_p}{\varepsilon_p + 2} E.d_p^2 \tag{9}$$

Here, we denote: ε_0 –dielectric constant of free space ($C^2/N.m^2$), ε_p –dielectric constant of the particle, E –local electric field intensity (V/m), d_p –particle diameter (μm).

- Gravity Force

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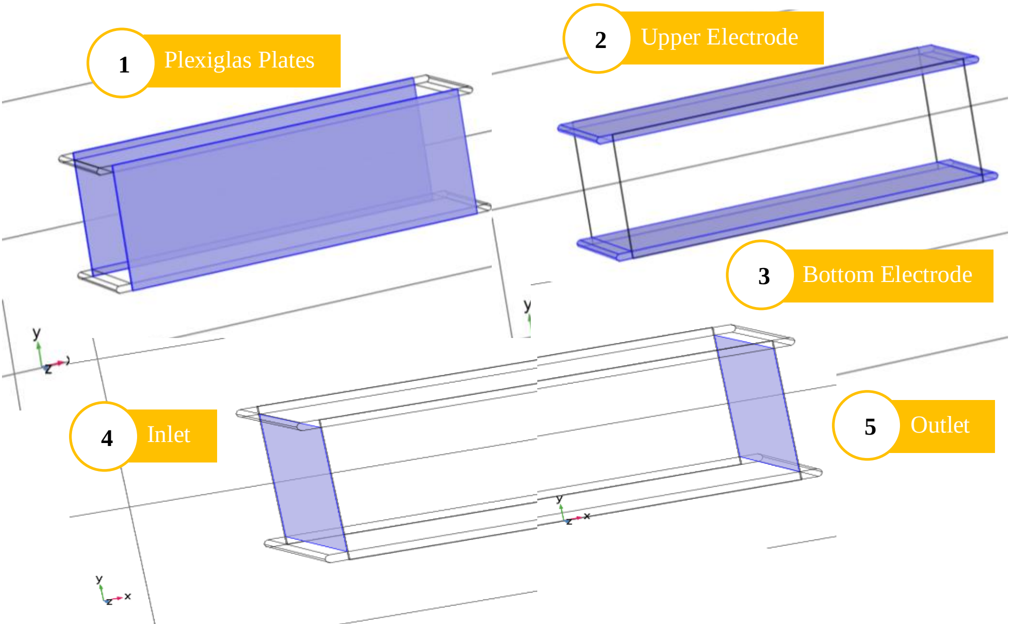
$$F_g = m_p g \frac{\rho_p - \rho}{\rho_p} \tag{10}$$

Here, we denote: m_p –particle mass (kg), g –acceleration due to gravity (m/s^2), ρ_p –density of the particle (kg/m^3), ρ –density of the gas (kg/m^3).

2. *Boundary Settings*

The boundary conditions for velocity components: Uniform velocity is specified at the inlet of magnitude 1 m/s for x-direction, pressure, electric potential and particle properties between two parallel plates separated with air gap are given as



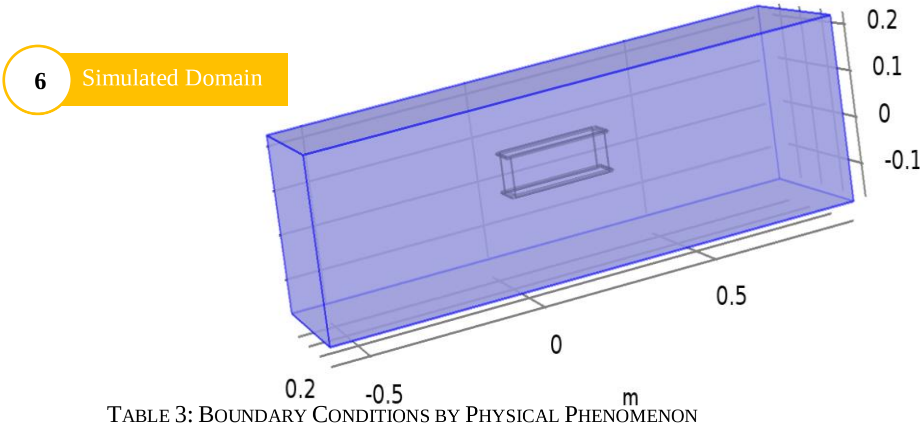


TABLE 3: BOUNDARY CONDITIONS BY PHYSICAL PHENOMENON

Physics (Modules)	Domain 1	Domain 2	Domain 3	Domain 4	Domain 5	Domain 6
Electrostatics	Charge Conservation	V_0=Vdc	Ground			Zero Charge
Laminar Flow	Wall: No Slip	Wall : Slip	Wall: No Slip	$U_0=V_{x0}$	p=5.10^{5}Pa	
Particle Tracing	Freeze	Bounce	Stick Upstream Particle Counter	$u0=V_{x0}$ Downstream Particle Counter	Freeze Particle Counter	

III. SIMULATION RESULTS AND DISCUSSION

A selection of numerical results from Comsol computations are described in the sections below:

A. *Simulation of Potential and Electric Field*

Electric field is the most important physical phenomenon in ESP because it provides the space charge needed for charging the particles.

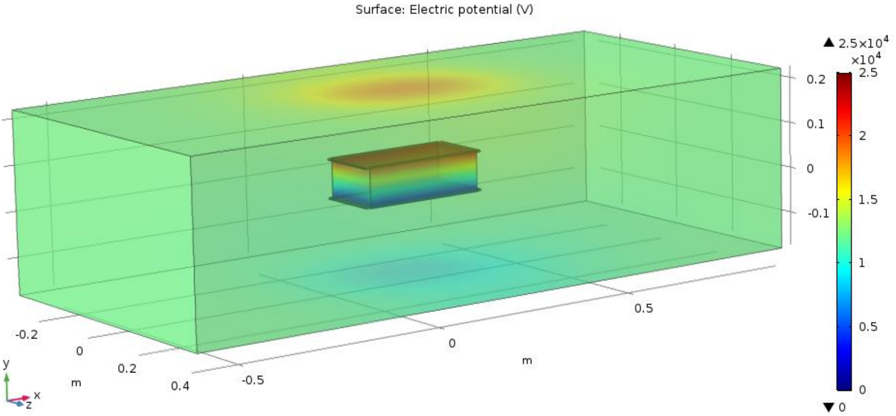


Fig. 2. Electric potential distribution in 3D channel

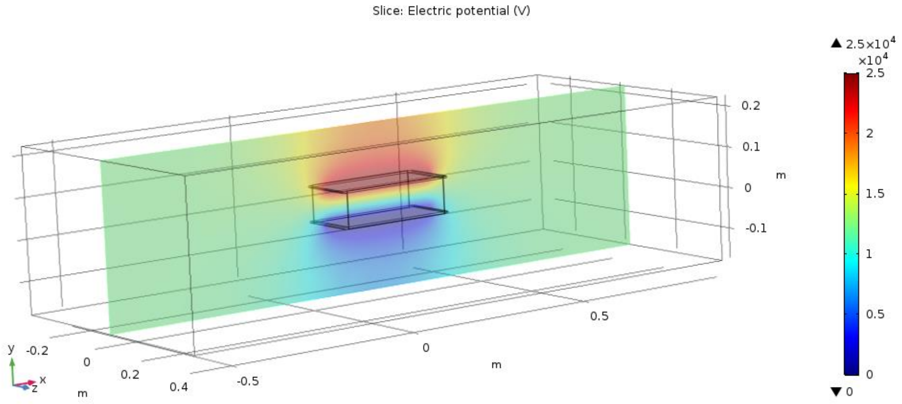


Fig. 3. Electric potential surface distribution in 3D channel

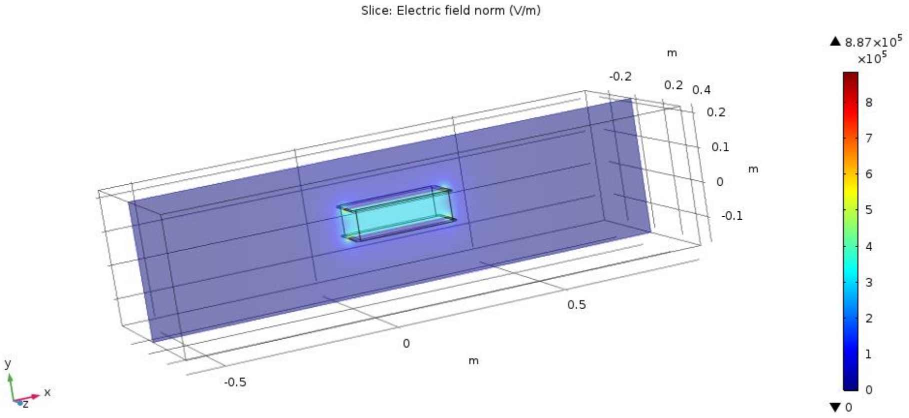


Fig. 4. Electric potential surface distribution in 3D channel

B. Simulation of Airflow velocity and pressure

The geometry formed by two parallel plates as shown in **Fig. 5** are assumed to be infinitely long the x-direction. Then the velocity depends on the x and y coordinates only. The velocity at the inlet is in the x-direction with a value $u_x = 1\,m/s$.

If the inlet velocity is high enough, the flow in ESP is turbulent but if the inlet velocity is very low, the flow in ESP without the corona discharge can be laminar.

You will see the flow fields distributions, like velocity and pressure in the chosen geometry; integration procedure to calculate drag force is also rather simple, as you will see below.

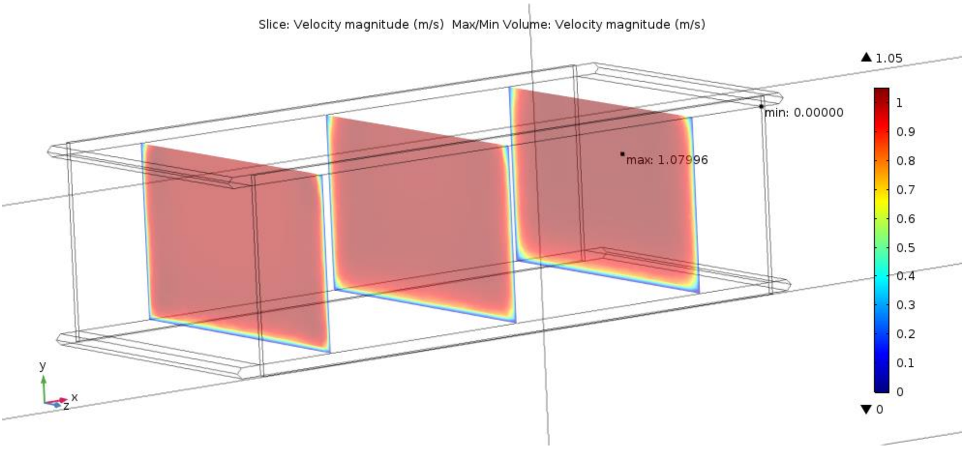


Fig. 5. Velocity profile between two parallel plates in 3D channel

C. Simulation of particle motion

In this case, we have to couple between different physical processes in ESP. The most important is the coupling between electric field and air flow because the electric field and charges that generate electrostatic force which affects and modify the air flow field.

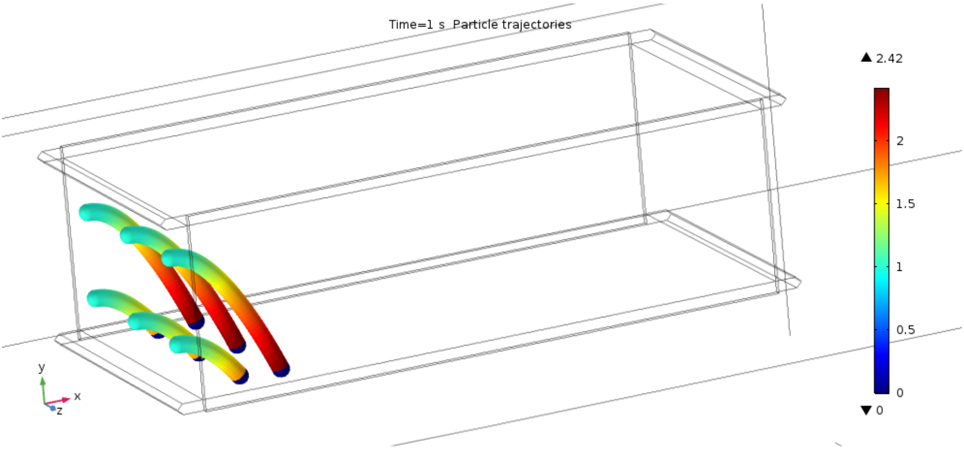


Fig. 6. Conceptual representation of computed trajectories of Portland cement particles in the presence of the Electric and Drag forces (plate to plate configuration).

The collection efficiency can be defined as the ratio of the number of particles collected by the collector plates to the total number of particles entering at the inlet. Because of the one way coupling assumption made and also the assumption that the particles do not interact, the collection efficiency is independent of the particle density, in these calculations[7]

To determine the collection efficiency for each case, number of particles are tracked in the flow field from the inlet of the ESP. These particles are assumed to be uniformly distributed and released with the same velocity as the air-stream from the inlet boundary. Any particle striking the collecting plate is assumed to be collected by the plate. The collection efficiency (η) is determined as follows [7]

$$\eta = \left(1 - \frac{N_{out}}{N_{in}}\right) \times 100 \tag{11}$$

where: N_{out} −Number of particles leaving the exit, N_{in} −Number of particles entering at the inlet.

On the collecting efficiency of ESP is analyzed, for the parameters given in each table.

Finally, we are presenting the results of our numerical simulation by summarizing them in tables below. These tables show the different values of electric field intensity, migration velocity and ESP precipitation efficiency in our configuration at by varying the applied voltage, charging rate, Initial Inflow velocity and number of dust particles at the entrance, all these cases are being studied and reported in all the tables that will follow.

TABLE 3: EFFECT OF THE APPLIED VOLTAGE ON THE ESP'S EFFICIENCY

Applied Voltage (kV)	Maximum Electric Field norm (V/m)	Maximum of the Migration Velocity (m/s)	Injected Particles	Collected Particles	Outgoing Particles	Efficiency
5	1.77×10^5	1.48	1010	934	76	92.48%
10	3.55×10^5	1.73	1010	948	62	93.86%
15	5.32×10^5	1.98	1010	957	53	94.75%
20	7.09×10^5	2.13	1010	962	48	95.25%
25	8.87×10^5	2.47	1010	962	48	95.25%

TABLE 4: EFFECT OF THE CHARGING RATE ON THE ESP'S EFFICIENCY

Charging Rate (C)	Maximum of the Migration Velocity (m/s)	Injected Particles	Collected Particles	Outgoing Particles	Efficiency
20% Q_S	1.48	1010	934	76	92.48%
40% Q_S	1.73	1010	948	62	93.86%
60% Q_S	1.98	1010	957	53	94.75%
80% Q_S	2.13	1010	962	48	95.25%
Q_S	2.47	1010	962	48	95.25%

TABLE 5: EFFECT OF INITIAL AIR FLOW ON THE ESP'S EFFICIENCY

Initial Inflow Velocity (m/s)	Maximum of the Migration Velocity (m/s)	Injected Particles	Collected Particles	Outgoing Particles	Efficiency
1	2.47	1010	962	48	95.25%
2	3.02	1010	964	46	95.45%
3	3.76	1010	964	46	95.45%
4	4.60	1010	964	46	95.45%
5	5.50	1010	964	46	95.45%

TABLE 6: EFFECT OF THE NUMBER OF PARTICLES PER RELEASE ON THE ESP'S EFFICIENCY

Number of Particles	Maximum of the Migration Velocity (m/s)	Injected Particles	Collected Particles	Outgoing Particles	Efficiency
20	1.48	1010	934	76	92.48%
40	1.73	1010	948	62	93.86%
60	1.98	1010	957	53	94.75%
80	2.13	1010	962	48	95.25%
100	2.47	1010	962	48	95.25%

IV. CONCLUDING REMARKS

A significant number of smaller precipitators use flat plates instead or wires both high-voltage and collecting electrodes are flat plates. This increases the electric field that can be used for particle collection and for high resistance particles.

The simulations previously described in the paper show the transition from stationary study to time dependent analysis.

The surface distribution of electric potential seen in **Fig. 2** shows the results as expected, it decreases when going from the top plate to the bottom plate and the electric field in Fig. 4 is still constant and uniform inside the inter-electrode space and it reaches a very high value $E = 8.87 \times 10^5\, V/m$ around the plates in the extremities.

At the beginning, when the dust particle has acquired 20% from the total saturation charge the Migration velocity was at 1.48m/s, it became really important comparing with the inlet velocity that we had chosen for the particle at the entry of ESP cell but by approaching at the maximum value of the charge required for saturation, the velocity does not increase much more and also by adding more and more particles at the entrance, the migration velocity will increase.

So, the charge acts much more on the drift velocity than what we thought.

Assuming that the gas flow force gives no net contribution to the transport of the particle towards the collecting plate. It's the electrostatic force that contribute for that which is on function of the particle's charge that have reached.

In the numerical simulation, coupling between different physical processes will consume much more time and effort. Therefore, it is necessary to investigate the influence of different couplings on simulation results and determine the conditions when some coupling should be included. These numerical computations provide insight in some basic phenomena governing the precipitator behavior and for this purpose it is very often enough with three-dimensional treatment.

V. FUTURE WORK

Electrostatic precipitator prototype showed encouraging particle removal efficiencies.

Model precipitator system in COMSOL to optimize parameters

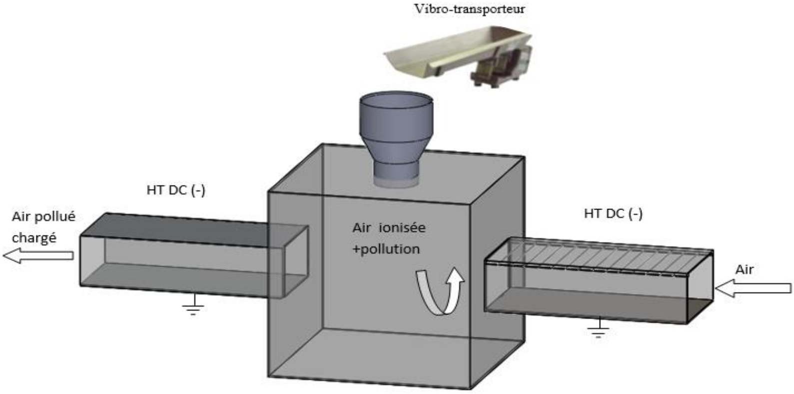
Quantify collection efficiency as a function of:

◦Voltage and corona current

◦Electrode length and diameter

◦Simulated atmospheric flow rate

The present study supported by a numerical simulation was carried out to test the possibility of filtration of fine particles previously charged in an ionized air. The particle charge chamber allows suction injection of powder and ionized air. In this case, the particles acquire an electrical charge due to the turbulence created inside the chamber. Once the particles charged, they pass through an intense electric field of plane configuration for capitation that we did in this article. The advantage of this new filtration technique is to be able to avoid the sparks and arcs caused by the particles inside the ESP in interaction with the electric discharge. Till now we have done the 4 part about conveying the particles after being charged in the previous stage.



REFERENCES

[1] Kazimierz Adamiak, Anatoly Malevanets: Total Variation Diminishing technique in numerical simulation of Trichel corona in air," Western University, London, Ontario, Canada, March 2017.

[2] Helena Nowakowska, Marcin Lackowski, Jerzy Mizeraczyk: Modelling of electrohydrodynamic (EHD) flow in a cylindrycal precipitator with eccentric wire electrode," Polish Academy of Sciences, August 2016.

[3] Ahmed Kasdi, Youcef Zebboudj, Hakim Yala: Simulation of Corona Discharge in DC Electrostatic Precipitator," University of Bejaia, Bejaia, Algeria, Canada, November 2015.

[4] Herek L. Clack: Simultaneous Removal of Particulate Matter and Gas-Phase Pollutants within Electrostatic Precipitators: Coupled In-Flight and Wall-Bounded Adsorption," University of Michigan, USA, September 2015.

[5] G.N. Sunil, Amaresh Dalal and Ganesh Natarajan: Computation of Flow Coupled with the Electic Field on Unstructured Grid ," Proceedings of the 5th International and 41st National Conference on FMFP, 2014.

[6] Maria Jędrusik, Arkadiusz Świerczok Wroclaw: Design Efficiency of ESP",University of Technology Poland.

[7] NARENDRA GAJBHIYE, V ESWARAN, A K SAHA, ANOOP KUMAR: Numerical calculation of particle collection efficiency in an electrostatic precipitator," Kanpur, India.