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Dynamic characteristics of Submicron particle deposited on the charged spherical collector

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ABSTRACT

This study explores the behaviour of oppositely charged submicron particles attracted by a pendant DC-charged spherical collector in still air. Quantitative analyses of dynamic particle behaviour is conducted. There are inertial, viscous, gravitational, electrostatic, and dielectrophoretic forces involved in analysis. Electrostatic forces cause submicron particles with opposite charges to move toward the charged collector. Electrostatic attractions and distance between collector and particle are tightly related. Particles have different initial attractions based on their position on the plate. It is determined that dielectrophoretic and gravitational forces are the weakest. The particle closest to the collector has the shortest drift time and greatest force, whereas the particle farthest from the collector has the longest drift time and least force. This study outlines charged particle movement and capture using a charged spherical collector.

Keywords: Charged spherical collector, electrostatic scrubbing, particle deposition, submicron particulate capture, aerosols

1. INTRODUCTION

Particulate matter (PM), a primary source of air pollution, is harmful to human health [1,2]. The "submicron zone" comprises of particles ranging in size from 0.1 to 1 micron. This poses a risk to the lungs of humans [3]. The collection process can be facilitated by inertial impaction, interception, gravity, electrostatic attraction, diffusion, and temperature gradient motion [4]. Inertia causes a particle carried by an air stream to follow the stream yet hit the obstruction[5]. Therefore, inertial forces are normally most significant for aerosol collection in scrubbers and high-speed filter. This is most dominating process for larger particles. In interception, the particle's trajectory may pass close enough to the collector for its surface to touch it. Similarly, slowly moving air particles can settle on a collecting surface due to gravity. Brownian diffusion becomes prominent below 0.1 micron[6]. However, submicron particles are not affected by inertia or diffusion. Due to their poor inertial characteristics and low mobility, submicron particles are difficult to remove from gas streams. In this size range, charged collector scrubbing is necessary due to the effectiveness of electrical interactions. Impact scrubbing that is electrically augmented increases the relative velocity between the collector and the particles [7]**.** Consequently, their likelihood of capture increases. The schematic of the different capture mechanism is shown in Figure 1.

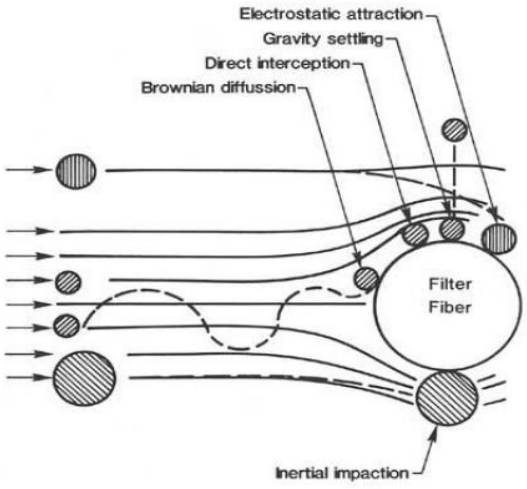


Figure1: Particle Capture Mechanism [8]

Inertia, electrostatic forces, and fluid friction are the primary factors that govern the outcomes of fine particle collisions with collectors (and are captured). In order to have a conceptual understanding of this topic, it is required to use equation of motion to determine the characteristic displacement, acceleration, and drift time of the particulate matter toward the collector. This study investigates how electrostatic forces, gravitational forces, dielectrophoretic forces, and viscous forces all influence the trajectories of individual particles. Consequently, the purpose of this work is to investigate the

fundamental effects of electrostatic charge on fluid dynamics, particle movement, and collection by a spherical charged collector.

2. LITERATURE REVIEW AND OBJECTIVE

Particles of submicron size in the Green's-Field gap or the accumulation mode make up a large portion of particulate matter. According to observations made by Jaworek et al., submicron-sized particles whose mobility is controlled by air drag or molecular forces are extremely challenging to capture. Therefore, the inertial force has no effect on the dynamics of the particles [9]. This results in a significant decrease in the deposition efficiency of conventional particle removal systems such as wet scrubbers and cyclones [10]. In a similar study, C.W. Lear et al. found that the inertial impact and diffusion of submicron particles had minimal impact. Therefore, the effectiveness of electrical interactions, electro scrubbing is a viable option for particles of this size range [7]. Additionally, Ziwen Zuo et al. discovered that due to electrostatic forces, particles actively deposit on charged droplets, therefore extending the collection region of a single droplet through inertial collision [11]. The remarkable efficiency of electrostatic wet deposition has been demonstrated both theoretically [12–20] and practically [21–26] in previous research.

In a significant number of earlier studies [27-30], researchers explored the particle trajectories as well as the collection efficiency of charged collectors. Lee et al. examined charged particle trajectories in a Lagrange reference frame using a discrete phase model (DPM) that incorporated interception as an important deposition mechanism. They then used the DLVO theory to calculate the interaction energies between particle and collector surfaces [27]. In a similar manner, Zuo et al. performed a numerical analysis of the paths of charged particle trajectories around a charged collector while taking into consideration three different impact modes. In addition to this, the trajectories that were calculated numerically agreed with his experimental finding [28]. In a similar manner, A. Jaworek et al. examined aerosol particle trajectories with the aid of his numerical model for a limited range of the Coulomb number and the Reynolds number [29]. Their primary objective was to determine the collision trajectories. As a direct consequence, A. Jaworek again conducted an experimental investigation of the particle trajectories in order to validate the previously mentioned numerical model [30]. Furthermore, many researchers have incorporated various forces into their numerical models to predict collection efficiency and particle trajectories, but the evolution of the dynamic characteristics of individual particles striking around the circumference of collector still have not been explored. These findings come from research that ranges from the most recent to the oldest studies [6,11,29,31]. The knowledge of drift time, characteristic response to respective forces under consideration will provide insights into how the location or position of a particle placed in a field that is not uniform affects the capture of an individual particle by a charged pendant collector. Therefore in order to address these research gaps, the present study leverages a previously developed mathematical model [11]. Under the impact of a non-uniform electric field, the model will enable us in getting insight into the dynamic characteristics of a particle initially placed at various positions within the computational domain.

3. METHODOLOGY

This section explains the configuration of the model followed by the set of governing equations.

3.1 Model Geometry

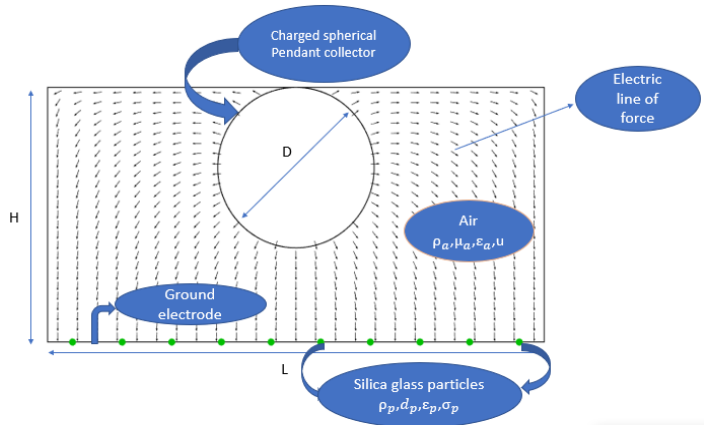


Figure2: Model geometry representation with particles at the bottom at t=0. (All dimensions in mm)

Figure 2 shows the model schematic, which depicts a pendant charge collector of diameter *(D)* creating a non-uniform electric around it. The collector is positioned in still air (i.e., u=0), which has density ($\boldsymbol{\rho_a}$), dynamic viscosity ($\boldsymbol{\mu_a}$), and relative permittivity ($\boldsymbol{\varepsilon_a}$). Silica glass particles with dimension ($\boldsymbol{d_p}$), density ($\boldsymbol{\rho_p}$), relative permittivity ($\boldsymbol{\varepsilon_p}$), and electrical conductivity ($\boldsymbol{\sigma_p}$) are randomly distributed across the base of the model across a length *H*. The shortest distance between the ground electrode and the collector's base is *H-D*. Because particles have opposite polarity charges, they drift towards the collector along the electric line of force and thus get captured.

3.2 Basic governing equations

The numerical approach follows the movement of particles in the gas phase without considering particle interactions. The flow of air is laminar, Newtonian, and incompressible. The fundamental governing equations of air flow are mass and momentum conservation equations.

$$\rho_a \nabla u_a = 0 \tag{1}$$

$$\rho_a (u_a . \nabla) u_a = \nabla . [-p_a I + u_a (\nabla u_a + \nabla u_a^T] + \rho_a g \tag{2}$$

Similarly, the solution for electric field is determined by applying Gauss' law of electrostatics to the entire domain The necessary equation are as follows

$$\boldsymbol{\nabla . (\varepsilon_0 \varepsilon_r V) = 0} \tag{3}$$

$$\boldsymbol{E = -\nabla V} \tag{4}$$

Furthermore, each particle moves independently from the others, Newton's equation of motion may be used to trace the trajectories of each of these particles.

$$\frac{dx_p}{dt} = u_p \quad (5)$$

$$m_p \frac{du_p}{dt} = F_D + F_G + F_{DEP} + F_E \quad (6)$$

Where,

$$F_D = \frac{1}{\tau_P} m_p(u - u_p), \text{ were, } \tau_p = \frac{\rho_p {d_p}^2}{18\mu} \quad (7)$$

$$F_G = m_p g \frac{\rho_p - \rho}{\rho_p} \quad (8)$$

$$F_{DEP} = 2\pi r_p^3 \epsilon_0 (\varepsilon_a) * (\frac{\varepsilon_a - \varepsilon_p}{\varepsilon_a + 2*\varepsilon_P}) \nabla | E |^2 \quad (9)$$

$$F_E = Q_P E \quad (10)$$

Table 1: Values of parameter involved in analysis

Parameters	Value
Density of air (ρ_a)	1.2 kg/m^3
Dynamic viscosity of air (μ_a)	1e-5 Pa-s
Relative Permittivity of air (ε_a)	1
Density of Particles (ρ_p)	1000 kg/m^3
Diameter of particles (d_p)	10µm
Relative permittivity of particles (ε_p)	7.6
Electrical conductivity of particles (σ_p)	1E-13 S/m
Electrical Potential of collector(V_0)	1000 V
Charge on Particle (Q_P)	4.75e-16 C
Diameter of spherical charged collector(D)	1.26 mm
Distance from hinge point of collector to the particle plate(H)	2 mm
Span of collector plate (L)	4 mm

4. RESULTSANDDISCUSSION:

4.1 Validation of Results:

To validate the numerical model, the existing experimental data of Zuo et al. [11] is compared. The numerical data for particle velocity agrees quite well with the existing experimental data. The Pearson correlation coefficient between numerical data and experimental data is 0.9261, indicating a strong correlation between experimental and numerical data.

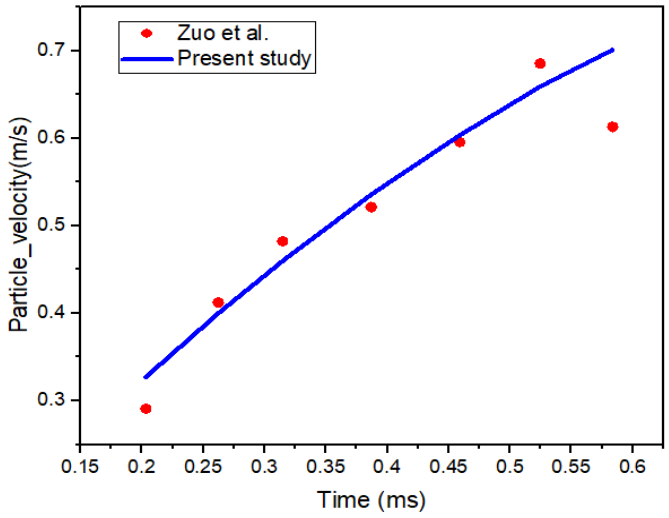


Figure 3: Particle velocity approaching charged collector compared experimentally and numerically

4.1 Electric Potential and Electric field norm distribution within the domain:

The potential distribution and electric field distribution around the pendant collector are given by the solutions of equations (3) and (4). Solving the Laplace equation for electric potential (V) inside the given domain yields the potential distribution. As indicated in Figure (2), the spherical collector's boundary was held at a constant potential (V_0), and the flat plate electrode was grounded. The distribution of the electric field (E) is determined by taking the gradient of the scalar electric potential (V) shown in Figure 4.

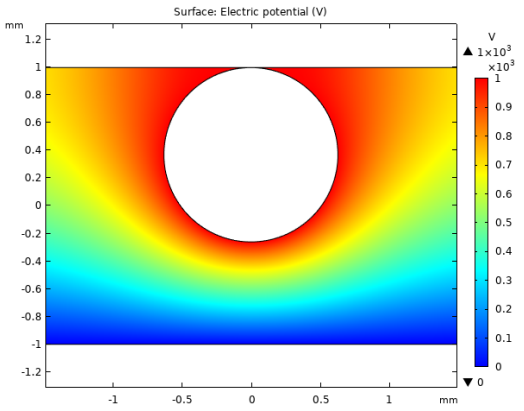


Figure 4: Electric potential distribution due to charged collector

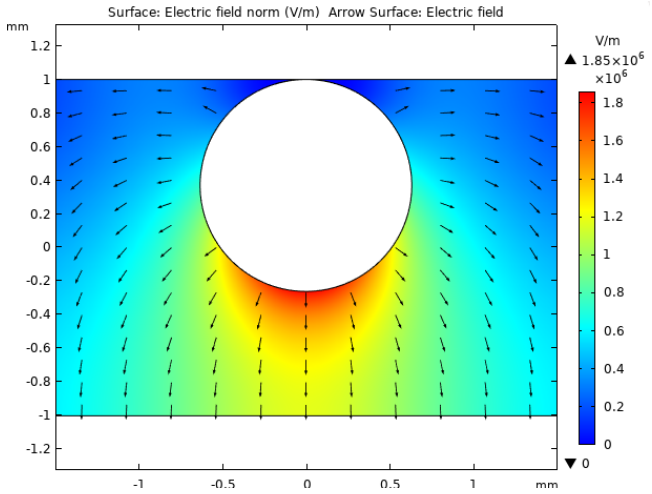


Figure 5: Electric field norm distribution due to charged collector

4.2 Trajectories of particle drifting towards charged collector

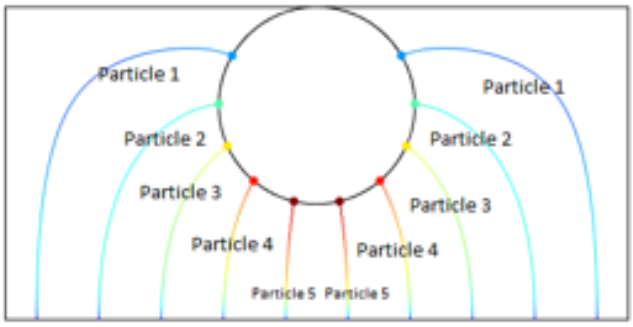


Figure 6: Charged collector particle trajectories

The trajectory of particles attracted by a spherical charged collector is depicted in the figure (Figure 6) above. Each particle is assigned a unique index, which aids in explaining the particle's kinematic and dynamic characteristics. The particle index on each symmetrically half side is kept similar because they will all behave similarly in terms of magnitude.

4.3 Analysis of forces acting on particle drifting towards the charged collector:

4.3.1 Analysis of norm of Electrostatic forces:

Each particle encounters a varied amount of electrostatic force due to non-uniform electric field distribution. Based on the initial position of particle on collection plate or ground electrode, particle 5 will experience greatest electrostatic force throughout its course, while particle 1 would experience minimal electrostatic force. Figure 5 shows that the electric field norm is significant along the lower portion of collector. As a result, particles (Particle 3-5) in the region of strong electric field experience the strongest electrostatic force relative to particles (Particle 1-2) lying farther away on the ground plate with respect to collector

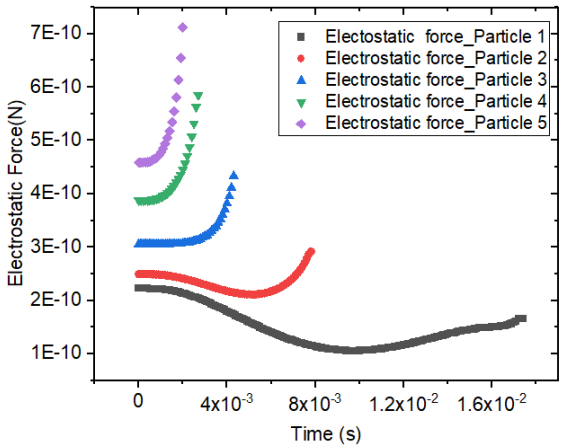


Figure 7: Evolution of Electrostatic Force acting on each particle along its trajectory

Furthermore, the change in the strength of the electric field norm is directlyrelated to whether the electrostatic force on each particle increases or decreases along its trajectory. Therefore, Figure 5 makes it clear how the electric field norm changes along the electric line of forces, and Figure 7 shows how the electric field variation affects electrostatic forces along the particle trajectory.

4.3.2 Analysis of magnitude of viscous drag along the particle trajectory

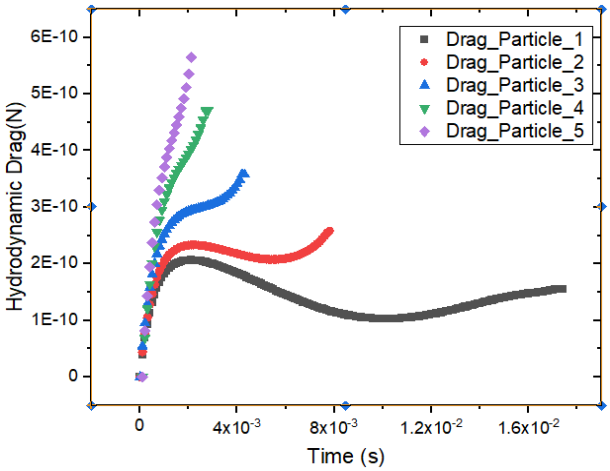


Figure 8: Evolution of drag force acting on each particle along its trajectory

Figures 7 and 8 show that the scale of drag force acting on a particle is nearly identical to electrostatic force. As a result, viscous drag plays a significant role in determining a particle's fate. Since the air is still, the typical fluctuation of drag force will be exactly proportional to the magnitude of particle velocity. The drag force curves for particles 3, 4, and 5 have inflection points at 0.017, 0.014, and 0.013 seconds, respectively. This is because the value of net positive

difference between electrostatic and viscous drag attains minima which compels the slope of acceleration to change from negative to positive. It implies that the velocity of particles 3, 4, and 5 will continue to increase with time until they are trapped, hence increasing the magnitude of drag force which is obviously consistent with Figure 8.However, after 0.021 seconds, the net difference in magnitude of electrostatic and drag forces becomes negative for particles 1 and 2. As a result of the decrease in particle velocity magnitude after 0.021 seconds, drag force displays a declining pattern. After a while, the difference in electrostatic and drag force magnitude becomes positive, causing the drag force to increase again until the particle is captured.

4.3.3 Analysis of Dielectrophoretic force:

Figure 9 shows that the scale of DEP force is an order of magnitude lower than that of drag and electrostatic force. As a result, the DEP force plays allow influence in particle capture However, particles closer to the collector experiencegreater DEP force than particles farther away on the collecting plate. In a stronger electric field zone, for particle 3,4,5 DEP will aid in overcoming gravitational force after liftoff, whereas for particle 1 and 2 it will be too weak to even overcome gravity force.

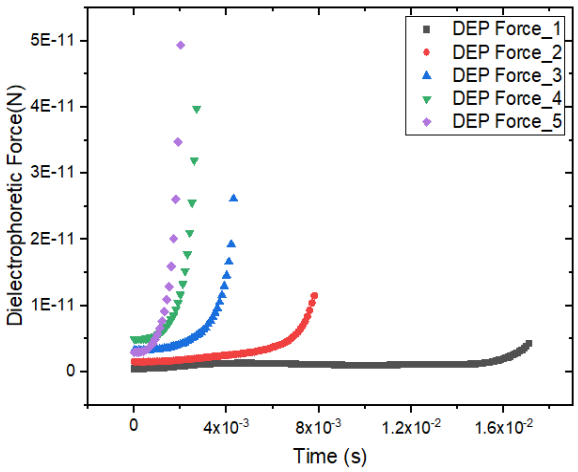


Figure 9: Evolution of Dielectrophoretic force acting on each particle along its trajectory

4.3.4 Analysis of Gravitational force

Gravitational forces are two orders of magnitude less significant than electrostatic and drag forces, and thus have little role in particle fate.

5 CONCLUSIONS

The present study illustrates how a particle behaves dynamically with respect to each of the forces that are being taken into consideration. According to the results of the analysis, the electrostatic and viscous drag are the fundamental forces that determine the trajectory of the particle. Both dielectrophoretic forces and gravitational forces have a negligible impact. Particles which are' located most closely to the collector, is subjected to the greatest electrostatic and drag forces, whereas particles located farther are subjected to the least amount of force. Because the particles' starting velocity was zero, there will be zero viscous drag at the moment of take-off. Consequently, the electrostatic attractive force that a particle experience will be at its highest value, and it will drift toward the collector with its highest value of initial acceleration while it is being lifted off the ground. Based on this, we are able to conclude that electrostatic force is the single key reason for the lifting of particles. In light of the fact that the particles have a size of submicron, the path that they take will be along the electric line of forces. However, particles of a bigger size will continue along their inertial trajectory and depending on where on the collecting plate they were first located, they may or may not be collected.

NOMENCLATURE

ρ_a	Density of air	[kg/m^3]
μ_a	Dynamic viscosity of air	[kg/m-s]
ε_a	Relative permittivity of air	--
ρ_p	Density of particle	[kg/m^3]
d_p	Diameter of particle	[mm]
ε_p	Relative permittivity of particle	--
σ_p	Electrical conductivity of particle	[S/m]
Q_p	Charge on a particle	[C]
E	Electric Field in domain	[V/m]
V	Electric Potential in domain	[V]
F_D	Viscous drag force	[N]
τ_P	Particle response time	[s]
F_G	Gravitational force	[N]
F_{DEP}	Dielectrophoretic force	[N]
F_E	Electrostatic force	[N]

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