Evaluation of coulomb force contribution on the filtration of aerosols using a well-characterized metallic grid

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EVALUATION OF COULOMB FORCE CONTRIBUTION ON THE FILTRATION OF AEROSOLS USING A WELL-CHARACTERIZED METALLIC GRID

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RESUME
Nous présentons une méthodologie expérimentale et numérique grâce à laquelle nous pouvons comparer les efficacités de filtration en prenant en compte une description précise de la force électrostatique entre une particule sphérique et une fibre.

ABSTRACT
We present an experimental and numerical methodology through which we can compare the filtration efficiencies taking into account a precise description of the electrostatic force between a spherical particle and a fiber.

MOTS-CLÉS : aérosol, filtration, électrostatique / **KEYWORDS:** aerosol, filtration, electrostatic

1. INTRODUCTION

The filtration of aerosols is of significant interest in a number of environmental, health, and safety applications including mitigating indoor and outdoor air pollution, reducing the transmission of respiratory viruses, and preventing dissemination of aerosolized hazardous materials. We are particularly interested in the filtration of radioactive aerosols, which may be produced from fires, leaks, or general decommissioning processes of nuclear energy facilities.
The role of electrostatic effects on the efficiency of a clean filter has been evaluated theoretically by analytically determining the trajectories of particles around a single fiber while accounting for electrostatic forces [1,2,3]. However, rigorous quantitative comparison of the electrostatic filtration efficiency between theory and experiments has never been achieved due to the complexity of standard filters.
In our experiments, we control the properties of both the aerosol particles and the filter media. To control the filter properties, we use a metallic grid with uniform fiber diameter and spacing and we control the fiber charge by applying a potential to this metallic grid such that the electric field distribution in our system is well-defined. We then develop particle trajectory simulations based on the fundamental forces acting on particles as they flow across an individual fiber representative of a fiber in the high-voltage metallic grid. All parameters in our simulation have a direct basis from our experimental system i.e. *no fitting parameters are used*. Finally, we compare the electrostatic filtration efficiency measured in our experimental bench to that determined from the simulations.

2. METHODS
2.1. Experiments

To generate a monodisperse aerosol stream with a controlled charge, we first aerosolize a solution of polystyrene latex (PSL) particles using a constant output collision type atomizer (TSI Model 3076) to produce a more or less monodisperse aerosol from 100 nm to 500 nm size. After generation, the aerosol passes through a diffusion dryer. Then, we use a differential mobility analyzer (DMA) (TSI Electrostatic Classifier Model 3082) to refine the aerosol size distribution of the PSL particles in the aerosol stream by selecting particles based on their electric mobility. Only particles within a narrow range of electric mobilities pass through the DMA such that the particles exiting the DMA are monodisperse and are charged with $1e^-$ (the particles have negative polarity). The schematic of the experimental system is depicted in Fig. 1.
We develop a filter with well-characterized geometry and electrostatic potential, as depicted in Fig. 1. The filter assembly consists of three metallic grids in series which are electrically insulated from each other using polyether ether ketone (PEEK) spacers. The fibers of the metallic grids have a diameter of D_f = 100 µm and edge-to-edge spacing of h = 250 µm. The PEEK spacers are annuli with inner diameter of 35 mm, outer diameter of 47 mm and thickness of 11 mm such that the metallic grids are separated from each other by d = 11 mm and the filter cross sectional diameter exposed to the aerosol stream is 35 mm. The middle grid is connected to a positive high-voltage supply and the outer two grids are connected to electrical ground such that the electric field in the filter assembly is well-characterized. The filter assembly is placed inside a standard conical metallic 47 mm filter holder, which is connected to electrical ground.

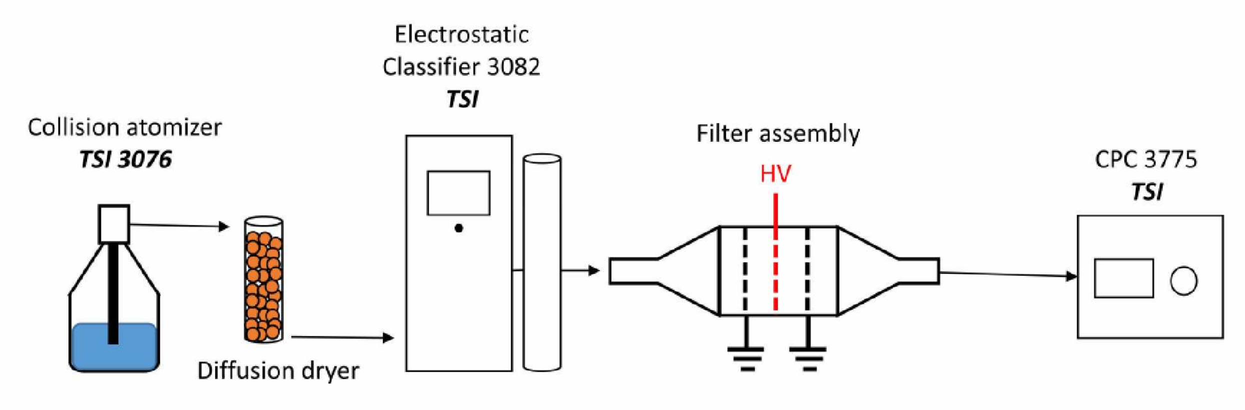

Figure 1. Schematic of experimental system. After the Electrostatic Classifier 3082, the aerosol is composed of monodisperse, singly charged PSL particles. The electric potential of the metallic grid is controlled using a high-voltage supply.

We measure the aerosol concentration when no voltage is applied to the center grid of the filter assembly, $C_{V=0}$, such that mechanisms of particle capture by Brownian diffusion, interception, inertial and image force capture are accounted for. Then, we apply voltage to the center grid of the filter assembly and measure the aerosol concentration, $C_{V>0}$; here, the significant mechanisms of particle capture are the previous ones as well as attractive coulombic forces between the negatively charged particles and positively charged metallic grid. Assuming the mechanical and coulombic mechanisms of particle capture are entirely independent (i.e., the filtration efficiency due to former is the same with and without voltage applied), the ratio $P_{coul}^{exp} = C_{V>0}/C_{V=0}$ represents the penetration of particles through the metallic grids only due to coulombic interactions.

2.2. Simulation

We simulate the trajectories of particles, using COMSOL Multiphysics, based on the fundamental forces acting on the particles as they flow around a single fiber and relate the single fiber capture efficiency in our simulation to the total aerosol penetration through the full metallic grid. Our simulation cell is characteristic of a fiber within the center, high-voltage, grid of our experimental filter assembly.
In simulating the particle trajectories, we consider drag force as well as coulombic force between the particle and fiber. First, we use the Navier-Stokes equation to determine the fluid flow field and Poisson's equation to determine electrostatic potential field in the system. The forces due to airflow are then calculated using Stokes law together with the fluid flow field, and the coulombic forces are calculated from the gradient of the electrostatic potential field. We assume the particles have no effect on the fluid flow and potential field, and the fluid velocity and electric field at the center of the particle are used to calculate the drag force and coulombic force respectively.

3. RESULTS

Figure 2 shows the experimental and simulation results for penetration through the filter assembly as a function of the applied potential difference between the high-voltage grid and grounded grids. We note that in all data presented, aerosol particles have one negative elementary charge, the middle metallic grid has a positive applied potential, and the metallic grid has fiber diameter of 100 µm and spacing of 250 µm. We emphasize that all parameters used in our simulation have values taken from our experimental system i.e. *no fitting parameters are used*. As shown, the penetration decreases as the applied potential difference increases. This effect occurs because the attractive forces between the particles and fibers increase with greater applied potential differences.

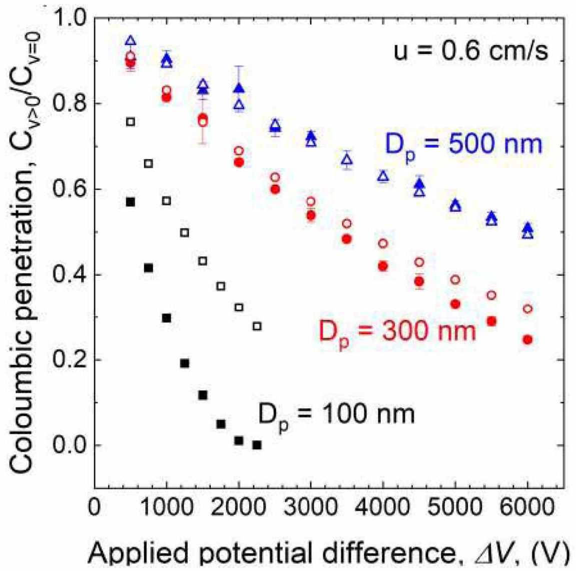

Figure 2. Coulombic penetration as a function of applied potential difference at a constant mean velocity u = 0.6 m/s for three particle diameters: D_p = 100 nm (black), D_p = 300 nm (red), D_p = 500 nm (blue). Filled symbols are for experiments and open symbols for simulations.

The experiments and simulation are in excellent agreement for particle diameter equal to 500 nm. For the smaller sizes (300 nm, 100 nm), we observe a discrepancy between experiment and simulation which enlarge according to potential difference applied to the grids. It should be noted that Brownian motion is not taken into account in the simulation; nevertheless, this fact cannot explain the discrespancies, especially as the difference between experiments and simulation increases with enhanced voltage. Further investigations will be necessary to properly interpret these differences; in particular on deposition inside the grids holder system, on the slip correction factor used in simulations or on more tricky phenomenon like interaction between interception and diffusion.

4. CONCLUSIONS

To the authors' knowledge, the experimental methodology in the present work is the first to control all aspects of the filter media and aerosol as to achieve comparison for fiber electrostatic filtration efficiency with simulations without any fitting parameters. As such, the experimental and simulation methodologies developed here provide valuable tools to address remaining open questions in electrostatic filtration from a fundamental, rather than empirical, perspective.

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