

Numerical Investigation of Collection Efficiency of Virtual Impactor with Electro-Aerodynamic Lens

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전기-공기역학적 렌즈를 이용한 가상임팩터 포집 효율에 관한 수치적 연구

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ABSTRACT

An electro-aerodynamic lens for improving the performance of virtual impactor has been proposed in this study. ANSYS FLUENT *Release 16.1* was used for numerical analysis of virtual impactor with and without the electro-aerodynamic lens, used to collimate the incoming aerosol particles into a particle beam before injecting the particles into the virtual impactor. Particles supplied to the electro-aerodynamic lens were assumed to be highly charged. By using an aerodynamic lens before the virtual impactor, without any electrostatic effect, it was found that the cut-off diameter of the virtual impactor was reduced from 4.2 μm to 0.68 μm and that the fine particle contamination problem became more serious. However, by employing the combined electrostatic and aerodynamic effects, that is, by applying electric voltage potential to the electro-aerodynamic lens, the cut-off diameter was found to be further reduced to 0.45 μm and the fine particle contamination was eliminated.

Keywords : Aerosol(에어로졸), Virtual Impactor(가상임팩터), Collection Efficiency(포집 효율)

1. Introduction

Virtual impactors, due to their simple design and operation, are widely used for aerosol particle sampling. Virtual impactors sample particles by accelerating them through a nozzle towards the outflow sections, known as major flow section and minor flow section. A small fraction of total inlet

flow (usually 5% to 20%) containing particles with aerodynamic diameters larger than a specified size, that is a cut-off size, is collected at the minor flow section, while particles with diameters smaller than the cut-off size are collected at the major flow section. The concept of virtual impactor was first proposed by Hounam and Sherwood^[1], and was further improved by Conner^[2], Dzubay and Stevens^[3], and Forney^[4]. The performance of virtual impactor is usually evaluated in terms of cut-off

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size, wall loss, and fine particle contamination. The cut-off size determines the capability of virtual impactor to measure the desired size range of particles, and the fine particle contamination shows the inaccuracy in sampling.

Many studies have been performed to improve the performance of virtual impactors. Marple and Chien^[5] investigated the effects of various geometric and operating parameters, *e.g.* Reynolds number, and major to minor flow ratio, on the collection efficiency of virtual impactor. Wada et al.^[6] compared the performance of the plate impactor with that of the virtual impactor, and the latter showed better collection efficiency. Chen and Yeh^[7], and Loo and Cork^[8] improved the collection efficiency by replacing a round nozzle of virtual impactor with a rectangular slit nozzle. Chein and Lundgren^[9] investigated the effect of clean air on the collection efficiency of virtual impactor by introducing sheath flow along with the aerosols flow. Ding and Koutrakis^[10] performed an experimental study on round and slit nozzle virtual impactors, and showed that same physical laws and principles can be used to predict the performance of both types of virtual impactors. Lee et al.^[11] used an orifice upstream of slit virtual impactor and Heo et al.^[12] used a horizontal inlet, in order to improve the collection efficiency of virtual impactor.

In the above-mentioned studies, the virtual impactors were used for sampling micron particles, and no effort was made for eliminating fine particle contamination problem. However, we believe that virtual impactor performance can be further improved by making it capable of sampling submicron particles under normal pressure condition and by increasing the sampling accuracy through elimination of fine particle contamination in the minor flow. Therefore, in this study, we propose an electro-aerodynamic lens which uses the combined aerodynamic and electrostatic effects for collimating the incoming aerosol particles into a thin

particle-beam. The electro-aerodynamic lens is connected to the inlet of virtual impactor, so that the collimated beam of aerosol particles can be supplied to the virtual impactor for sampling. The performance of virtual impactor with and without the proposed electro-aerodynamic lens is determined through numerical analysis.

2. Numerical Method

A schematic of slit-nozzle virtual impactor considered for this study is shown in Fig. 1. The virtual impactor was modeled by considering the recommendations of Ding and Koutrakis^[10], and Lee et al.^[11]. The virtual impactor consisted of two nozzles, that is, acceleration nozzle and collection nozzle. The width of the acceleration nozzle was 1 mm, and that of the collection nozzle was 1.4 mm. The span of the acceleration nozzle was kept 10 times its width to ensure the application of two-dimensional analysis. The impactor inlet width was 6 mm. Fig. 2 shows the schematic of electro-aerodynamic lens proposed in this study. The inlet of the electro-aerodynamic lens was divided into two partitions for supplying clean air and aerosol flow separately. The outer electrodes were grounded and the central one was utilized as a high voltage electrode. The lengths of electrodes and partition were 41 mm and 10 mm, respectively, while the width of each inlet partition and the converging nozzle was 3 mm and 1 mm, respectively. The collection probe of the electro-aerodynamic lens was also connected to the ground and high voltage source to keep the aerosol beam collimated. The span of nozzle was kept 10 times its width, like the virtual impactor, for ensuring two-dimensional analysis. Fig. 3 shows a schematic of combined configuration of electro-aerodynamic lens and virtual impactor, considered in this study for performance

improvement.

The fluid flow simulation was performed by using a computational fluid dynamics (CFD) code, ANSYS FLUENT *Release16.1*, and a fluid magneto-hydrodynamic (MHD) module was utilized for incorporating the effect of electric potential along with fluid flow. Grid independence test was conducted for the geometries of virtual impactor and electro-aerodynamic lens to determine the optimum number of computational cells for the analysis. The optimum number of computational cells considered for the combined configuration of electro-aerodynamic lens and virtual impactor was determined to be about 67,000. Air flow in the electro-aerodynamic lens and virtual impactor was considered to be two-dimensional, steady, laminar, and incompressible. The Reynolds number at the nozzle of virtual impactor was kept lower than 2,000 and was calculated as:

$$Re = \frac{\rho_{air} W_{acc} U_{acc}}{\mu_{air}} \quad (1)$$

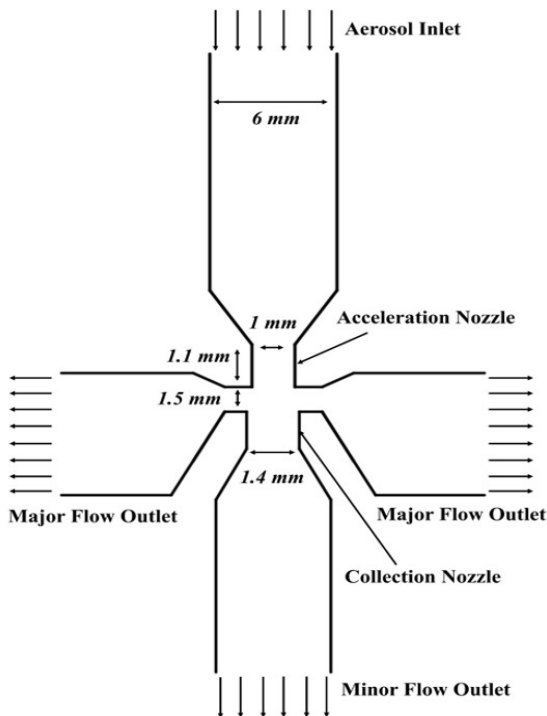


Fig. 1 Schematic diagram of a virtual impactor

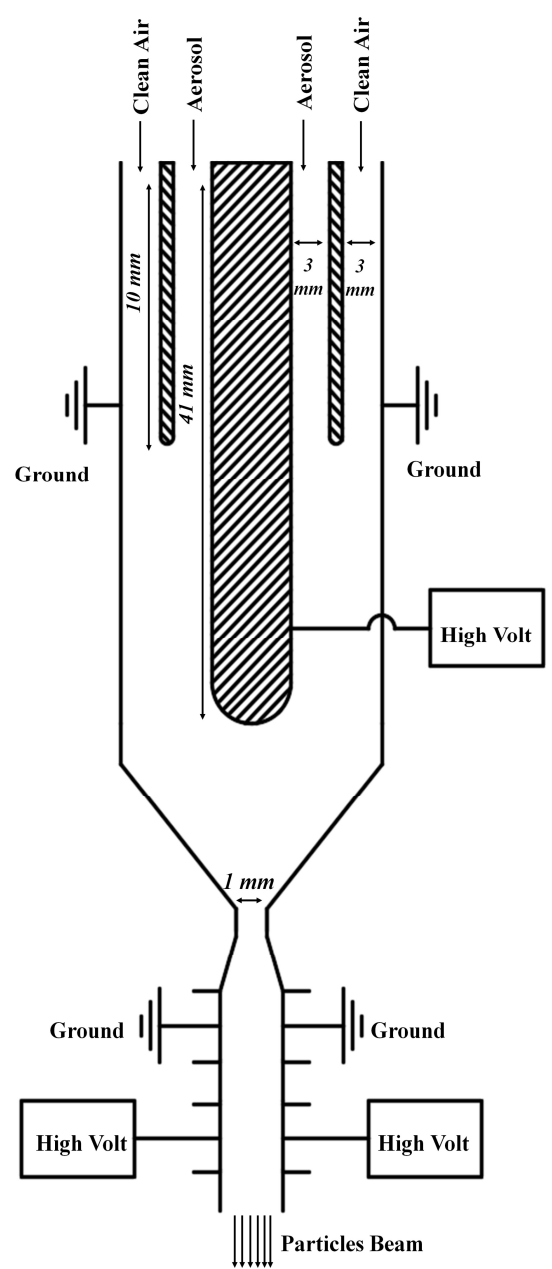


Fig. 2 Schematic diagram of an electro-aerodynamic lens

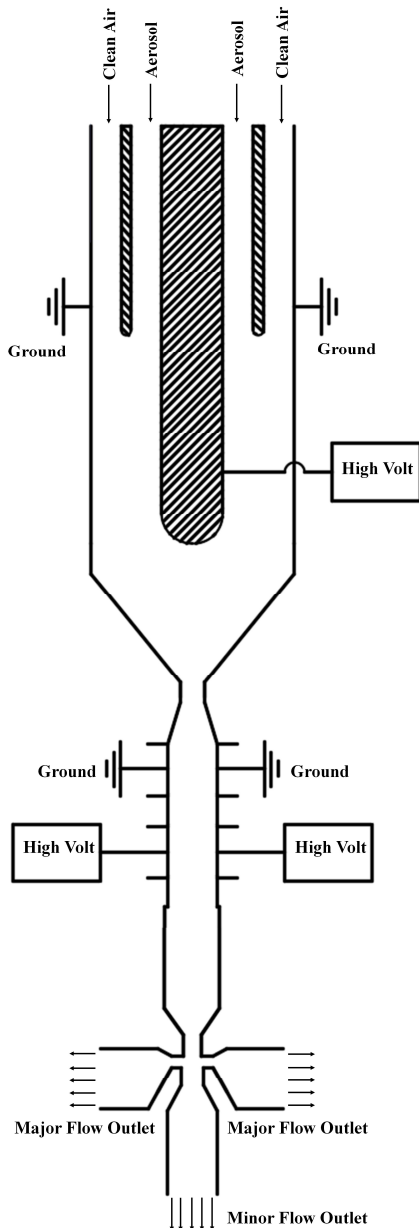


Fig. 3 Schematic diagram of virtual impactor with electro-aerodynamic lens

where ρ_{air} and μ_{air} are the density and viscosity of air, respectively, and W_{acc} and U_{acc} are the width of

acceleration nozzle and the average velocity through it, respectively. The properties of air at 20°C and 101.3 kPa were assumed for numerical analysis. A SIMPLE algorithm was used to couple velocity and pressure for solving energy, continuity, momentum, and electric potential equations. The convergence criteria were kept at 10^{-6} . The boundary conditions used for the numerical analysis were no-slip condition at the walls, velocity inlet at virtual impactor inlets, and pressure outlet at both major and minor flow exits. The flowrate ratio of minor flow to total flow, and that of major flow to total flow were kept at 0.1 and 0.9, respectively. Similarly, the boundary conditions considered for the MHD analysis of electro-aerodynamic lens were conductive at the electrode and insulation at all walls. Discrete phase model (DPM), provided in the FLUENT code, was used for calculating the trajectories of particles within the virtual impactor and the electro-aerodynamic lens. The DPM was based on Lagrangian reference frame. The DPM predicted the particle trajectories by assuming the effects of Brownian diffusion, charge density, Stokes' drag with slip correction, and gravitational settling. A uniform velocity profile with consistent particle number concentration was assumed at the electro-aerodynamic lens inlet. Particles with density of 1,050 kg/m³ and high charge level, that is, +50 per particle (Choi and Kim^[13]), were injected to the electro-aerodynamic lens with uniform spacing between the particles and at the same velocity as the inlet flow. Particles were assumed to be captured upon hitting the wall.

The numerical approach utilized for the analysis was validated by comparing it with numerical and experimental results obtained by Lee et al.^[11] An aerosol flowrate of 10.4 L/min at virtual impactor inlet was set for validation. To make sure the reduction of impactor cut-off diameter by the electro-aerodynamic lens, we reduced the total inlet flowrate to 5 L/min for further analysis. The

optimum inlet flowrates of clean air and aerosol at the lens inlet were determined as 1.5 L/min and 3.5 L/min, respectively. The electric voltage applied to the electro-aerodynamic lens was 2,000 V at both the inlet and the exit section of the lens. The term ‘aerodynamic lens’ was used to represent the electro-aerodynamic lens without electric voltage potential, while the term ‘electro-aerodynamic lens’ was used to signify the lens that converged particles by using both aerodynamic and electrostatic effects (see Fig. 2). Therefore, three different cases, that is, without any lenses, with aerodynamic lens, and with electro-aerodynamic lens, were considered for comparison. The collection efficiency of virtual impactor was calculated as:

$$\eta = \frac{N_{minor}}{N_{minor} + N_{major}} \times 100(\%) \quad (2)$$

where N_{minor} and N_{major} are the particle number concentrations at minor flow section and major flow section of the virtual impactor, respectively.

3. Results and Discussion

In order to validate our numerical method, we performed numerical analysis of the virtual impactor used by Lee et al.^[11] and compared our numerical results with their numerical and experimental data as shown in Fig. 4. The results of the present study were in good agreement with the outcomes of Lee et al.^[11], hence the present numerical approach could be used for further analysis. The total inlet flow rate used in the abovementioned analysis was 10.4 L/min, for which the impactor cut-off size was about 2.5 μm . According to Marple and Chien^[5], the cut-off size can be further reduced by increasing the inlet flowrate. However, as our target was to identify the capability of electro-aerodynamic lens for reducing the cut-off size, we reduced the total inlet flow rate to 5 L/min for further analysis.

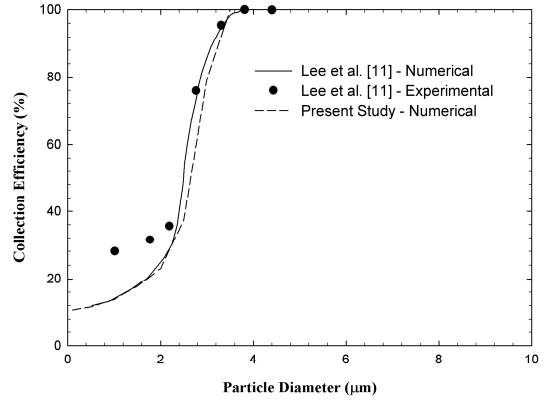


Fig. 4 Virtual impactor numerical method results validation for collection efficiency

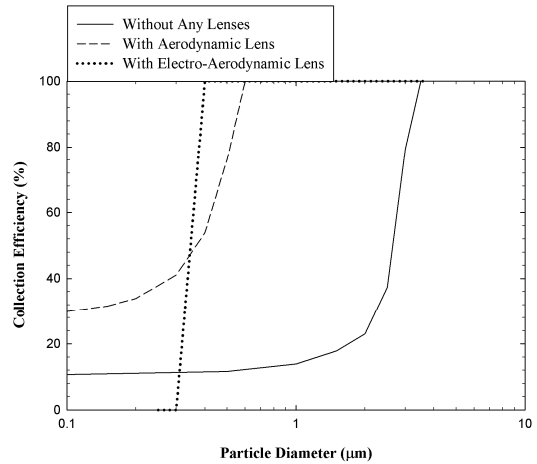


Fig. 5 Collection efficiency comparison of virtual impactor without any lens, with aerodynamic lens, and with electro-aerodynamic lens

Fig. 5 shows the comparison of virtual impactor collection efficiency achieved with and without using the aerodynamic lens. The cut-off size of the virtual impactor alone, that is, without any lenses, was 4.2 μm at an inlet flowrate of 5 L/min, while it was reduced to 0.68 μm by using the aerodynamic lens before the virtual impactor. In this case, the clean air injected at the inlet of the

electro-aerodynamic lens aerodynamically converged the incoming aerosol without using any electrostatic effect, by making aerosol particles move towards the centerline. As the aerosol particles were concentrated in the region near the centerline while they pass through the aerodynamic lens, most of the particles larger than the cut-off size were collected at the minor flow section without deflecting towards the major flow section, which significantly reduced the cut-off diameter. Similarly, the number of particles smaller than the cut-off diameter also increased in the minor flow, resulting in the increase of collection efficiency for particles smaller than the cut-off size. This means that the use of the aerodynamic lens caused an increase in fine particle contamination.

The aerodynamic lens improved the performance of virtual impactor in terms of the collection efficiency as abovementioned, but at the same time the significant rise in fine particle contamination has further deteriorated the impactor sampling accuracy. Hence, to overcome this issue, the virtual impactor was equipped with an electro-aerodynamic lens, which was used to converge particles into a thinner collimated beam by using both aerodynamic and electrostatic effects. The particles before being supplied to the virtual impactor were assumed to be highly charged. The collection efficiency of virtual impactor with and without the electro-aerodynamic lens was determined and compared, as shown in Fig. 5. It can be observed that by using the electro-aerodynamic lens, the cut-off size of virtual impactor was reduced from $4.2 \mu\text{m}$ to $0.45 \mu\text{m}$, and there was no fine particle contamination in the minor flow section, that is, very low or 0% collection efficiency for particles smaller than the cut-off size. The significant reduction in cut-off diameter was due to the much thinner particle beam obtained from the combined aerodynamic and electrostatic effects in the lens. Moreover, particles smaller than the cut-off size, due to their high

electric mobility, were attracted and captured by the central electrode, as a result, no fine particle contamination was observed in the sampling result.

Fig. 6 shows the trajectories of $0.5 \mu\text{m}$ particles in the virtual impactor for three different cases, that is, without any lenses, with aerodynamic lens, and with electro-aerodynamic lens, before the virtual impactor. It can be observed that, without any lenses, a lot of particles deviated towards the major flow, while some particles followed the minor flow, causing fine particle contamination. When the aerodynamic lens was used before the virtual impactor, the number of $0.5 \mu\text{m}$ particles, which were smaller than the cut-off diameter of $0.68 \mu\text{m}$, increased in the minor flow section, compared to the case without any lenses. Hence it caused a significant increase in fine particle contamination. When an electro-aerodynamic lens was used before the virtual impactor, particles smaller than the cut-off diameter of $0.45 \mu\text{m}$ was captured by the central electrode, while $0.5 \mu\text{m}$ particles could remain airborne and form thin collimated beam at the acceleration nozzle by making them sampled at the minor flow section of the virtual impactor. Therefore, the electro-aerodynamic lens was found to be helpful in increasing the capability of virtual impactor for sampling submicron particles and eliminating fine particle contamination problem.

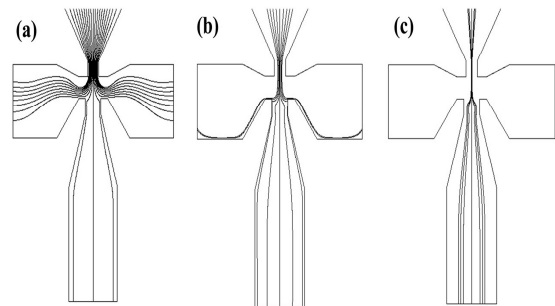


Fig. 6 Trajectories of $0.5 \mu\text{m}$ particles in virtual impactor (a) without any lens (b) with aerodynamic lens (c) with electro-aerodynamic lens

4. Conclusion

Numerical analysis was performed to investigate the performance of the virtual impactor with and without electro-aerodynamic lens. The electro-aerodynamic lens, proposed in this study, was equipped with three electrodes, *i.e.* two grounded electrodes and one high-voltage central electrode, across which electric voltage was applied for creating electric field within the lens. The performance of virtual impactor was determined by using the electro-aerodynamic lens before the virtual impactor. With the aerodynamic lens, the virtual impactor's cut-off size was reduced from 4.2 μm to 0.68 μm , but it increased fine particle contamination in the minor flow section. However, with the use of the electro-aerodynamic lens, the particles smaller than the cut-off size, which caused fine particle contamination, were attracted and trapped by the central electrode; moreover, the aerosol beam supplied to the virtual impactor was made further thinner by the combined electrostatic and aerodynamic effects in the lens, resulting in further reduction of cut-off size (down to 0.45 μm) and elimination of fine particle contamination in the minor flow section. Therefore, it is concluded that the electro-aerodynamic lens can be very effective in improving the sampling accuracy of virtual impactor not only by reducing fine particle contamination in the minor flow section but also by increasing the capability of virtual impactor for sampling submicron particles.

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