

Investigation of a Submicron-Particle Inertial Impactor for Size-Selective Inlet of the Electrical Mobility Spectrometer

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ABSTRACT

An inertial impactor is widely used for sampling, separating and measuring aerosol particles of aerodynamic size. In this study, a prototype of the submicron-particle inertial impactor for size selective inlet of the electrical mobility particle sizing instruments was designed, constructed and investigated. The effects of major design parameters on the cut-off diameter were analytically investigated including the aerosol flow rate, acceleration nozzle-to-impaction plate distance, and acceleration nozzle diameter. A prototype of the impactor was preliminarily tested experimentally to investigate the particle collection efficiency of the impactor and the deposited particles on the surface of the impaction plate inside the impactor. The combustion aerosol generator was used to generate a polydisperse carbonaceous diffusion flame aerosol in the size range of approximately 10 nm – 10 μ m for this experiment. It was shown that the theoretical 50% cut-off diameter decreased with increasing aerosol flow rate and also decreased with decreasing acceleration nozzle diameter. Finally, the results of the preliminary experimental tests and the photograph of particle deposited on the surface of the impaction plate inside the impactor was presented and also observed in this paper.

Key words: Particle aerosol, Inertial impactor, Size-selective inlet, Electrical mobility Spectrometer

INTRODUCTION

Inertial impactors have been widely used for many years for sampling and separating airborne aerosol particles of aerodynamic size for further chemical analysis because they are simple in construction with high separation and collection capabilities (Hinds, 1999). It consists of an acceleration nozzle and a flat plate, called an impaction plate. In inertial impactor, particles with sufficient inertia are unable to follow the streamlines and will impact on the impaction plate. Smaller particles will follow the streamlines and not be collected on the impaction plate. The aerodynamic particle size at which the particles are separated is called the cut-point diameter. Numerous extensive studies had been carried out in the past (May, 1945; Ranz and Wong, 1952; Andersen, 1966; Lundgren, 1967; Cohen and Montan, 1967; Mercer and Chow, 1968; Mercer and Stafford, 1969; Marple, 1970; Marple and Liu,

1974; Marple and Willeke, 1976; Dzubay et al., 1976; Markowski, 1984). In a later work, inertial impactors have been used extensively for measurements of micron or super-micron aerosol particle size distribution by mass known as an electrical low pressure impactor (ELPI) (Keskinen, 1992; Keskinen et al., 1992; Marjamaki et al., 2000).

In the electrical mobility particle sizing instruments, inertial impactors were also used to remove submicron-sized particles outside the measurement size range upstream of the instruments due to their contribution to multiple-charged aerosols (TSI, 2002; Intra, 2006; Intra and Tipayawong, 2006a, 2006b). These multiple-charged aerosols have the same electrical mobility diameter, and may therefore be detected on the same sensor. Consequently, the signal measured at a given sensor will be due to particles of different physical sizes. Even though inertial impactors have been widely studied for micron or super-micron aerosol collection, separation and measurement, submicron-particle inertial impactor for size selective inlet of the electrical mobility particle sizing instruments have not yet been studied extensively. So far, studies on submicron size selective inlet impactors were not carried out enough.

Therefore, an inertial impactor for upstream separating submicron size aerosol particles for the electrical mobility particle sizing instruments was designed, and theoretically and experimentally investigated in this study. The effects of major design parameters on the cut-off diameter were theoretically investigated. The parameters included the aerosol flow rate, nozzle-to-impaction plate distance and acceleration nozzle diameter. A prototype of the impactor was built and preliminarily tested experimentally. Finally, preliminary test results are also presented.

IMPACTOR DESIGN

The most important characteristic of an inertial impactor is the collection efficiency curve which indicates the percent of particles of any size which is collected on the impaction plate as a function of the particle size. According to Marple and Willeke (1976), for conventional inertial impactor, the aerosol flow rate, the acceleration nozzle-to-impaction plate distance and the acceleration nozzle diameter are the important parameters governing the performance of the inertial impactor. A schematic diagram of the inertial impactor used in this study is shown in Figure 1. The design of the impactor is based on the inertial impactor configuration of Marple and Willeke (1976). It consists of an acceleration nozzle and an impaction plate. The acceleration nozzle and the impaction plate are made of a stainless steel. In the inertial impactor, the aerosol flow is accelerated through an acceleration nozzle directed at an impaction plate. The impaction plate deflects the flow streamlines to a 90° bend. The particles larger than the cut-off diameter of the impactor impact on the impaction plate while the smaller particles follow the streamlines and avoid contact to the impaction plate and exit the impactor. A picture of the impactor used in this study is shown in Figure 2.

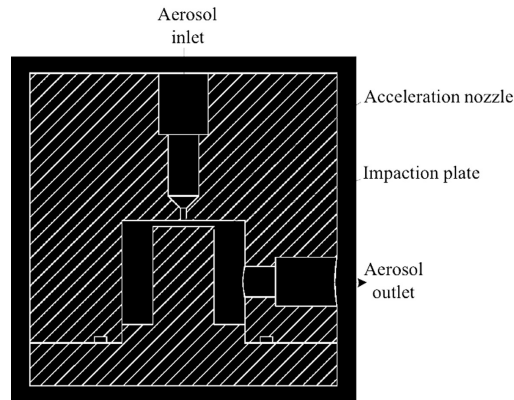


Figure 1. Schematic diagram of the submicron-sized particle inertial impactor.

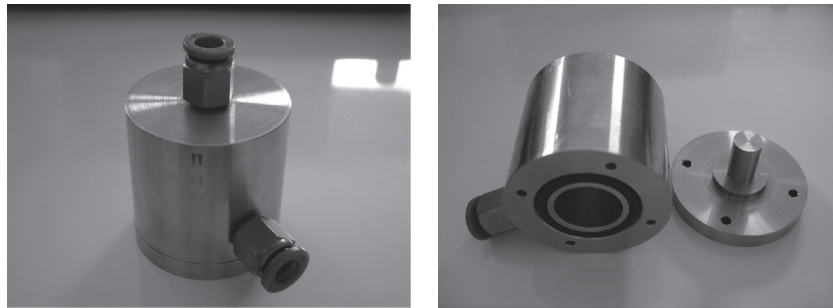


Figure 2. A picture of the submicron-sized particle inertial impactor.

The acceleration nozzle diameter can be calculated from the Stokes number (Stk). The Stokes number is a dimensionless parameter that characterizes impaction, defined as the ratio of the particle stopping distance to the halfwidth or the radius of the impactor throat. The Stokes number equation for a round jet impactor is defined as (Hinds, 1999):

$$\text{Stk} = \frac{\rho_p C_c d_p^2 U}{9\eta D}, \quad (1)$$

where ρ_p is the particle density, C_c is the Cunningham slip correction factor, d_p is the particle cut-off diameter, U is the mean velocity at the throat, η is the gas viscosity, and D is the acceleration nozzle diameter. Air density and viscosity are 1.225 kg/m^3 and $1.7894 \times 10^{-5} \text{ kg/m/s}$, respectively. Temperature of 294°K is used. For the round jet impactor, the expression of the average velocity within the round jets is given by the following equation

$$U = \frac{4Q}{\pi D^2}. \quad (2)$$

Substituting Equation 2 into Equation 1 gives

$$\text{Stk} = \frac{4\rho_p C_c d_p^2 Q}{9\pi\eta D^3} \quad (3)$$

Solving the above equation for the particle cut-off diameter at 50% collection efficiency, d_{50} , can be calculated by (Hinds, 1999)

$$d_{50} \sqrt{C_c} = \sqrt{\frac{9\pi\eta D^3 \text{Stk}_{50}}{4\rho_p Q}} \quad (4)$$

Because C_c is a function of d_{50} , Equation 4 cannot be conveniently solved for particle diameter. For conventional impactor, d_{50} can be estimated from $d_{50} \sqrt{C_c}$ using the following empirical equations (Hinds, 1999)

$$d_{50} = d_{50} \sqrt{C_c} - 0.078 \times 10^{-8}, \quad d_{50} \text{ is in m.} \quad (5)$$

This equation is accurate within 2% for $d_{50} > 0.2 \mu\text{m}$ and pressure from 0.9 – 1 atm (Hinds, 1999). Thus, the acceleration nozzle diameter is given by

$$D = \sqrt[3]{\frac{4\rho_p (d_{50} \sqrt{C_c})^2 Q}{9\pi\eta \text{Stk}_{50}}} \quad (6)$$

where Stk_{50} is the Stokes number of a particle having 50% collection efficiency. For the round jet impactor, Stk_{50} is 0.24, and the ratio of the acceleration nozzle diameter to the nozzle-to-plate distance is 1.0 (Marple and Willeke, 1976; Hinds, 1999). In this study, the 50% cut-off diameter $\geq 1 \mu\text{m}$ for the size selective inlet of the electrical mobility particle sizing instruments. The fractional particle penetration efficiency (P) of the impactor was determined as follows:

$$P(\%) = (1 - E) \times 100 \quad (7)$$

where E is the particle collection efficiency of the impactor, and it is determined from (Marjamäki et al., 2000)

$$E = \left[1 + \left(\frac{d_{50}}{d_p} \right)^{2s} \right]^{-1} \quad (8)$$

where s is the parameter affecting the steepness of the collection efficiency curve. In the present study, $s = 1$ is arbitrarily assumed for the steepness of the collection efficiency curve.

PRELIMINARY EXPERIMENTAL TESTING

In order to measure the particle collection efficiency, it is necessary to measure the particle concentration both upstream and downstream of the impactor.

For each particle size, the particle collection efficiency of the impactor was defined as:

$$E = 1 - \frac{C_{p, \text{down}}}{C_{p, \text{up}}}, \quad (9)$$

where $C_{p, \text{up}}$ and $C_{p, \text{down}}$ are the particle number concentrations in upstream and downstream, respectively. Unfortunately, particle size distribution of both upstream and downstream of the impactor was not measured because no aerosol sizer was available at the time of the experimentation. Thus, only particle number concentrations of both upstream and downstream of the impactor were preliminarily investigated using unipolar corona charging and electrostatic detection of highly charged particles (Intra and Tippayawong, 2008). The deposited particles on the surface of the impaction plate inside the impactor were also observed. A schematic diagram of the preliminary experimental setup used to investigate the collection efficiency of particles of the impactor and the deposited particles inside the impactor is shown in Figure 3. The combustion aerosol generator was used to generate a polydisperse carbonaceous diffusion flame aerosol for this experiment. Stable polydisperse aerosols with particle number concentrations of approximately $10^{12} - 10^{14}$ particles/m³ were obtained (Cleary et al., 1992). The particle size obtained by scanning electron microscopy (SEM) was in the range between approximately 10 nm – 10 µm. Figure 4 shows the particle morphologies of agglomerates obtained from the scanning electron micrograph, taken with a JEOL JSM-6335F Field Emission Scanning Electron Microscope, operated at 15 kV and magnification of 5,000X. In this study, the sampling aerosol flow rate was regulated and controlled by means of mass flow meter and controller with a vacuum pump and the flow rate ranging from 1.0 to 5.0 l/min. The particles were first dried with the diffusion drier. Thus, any remaining water was removed. Before aerosol particles entering the impactor, the particles were diluted and mixed with clean air, which had been filtered through a HEPA filter, in the mixing chamber. In the impaction plate, impaction surface was coated with an adhesive collection substrate to prevent particle bounce. Particle number concentrations of both upstream and downstream of the impactor were measured. In the measurement system, aerosol sample first pass through the unipolar corona charger that sets a charge on the particles and enter the ion trap to remove the free ions. After the ion trap, the charged particles then enter the Faraday cup electrometer for measuring ultra low current about 10^{-12} A induced by charged particles collected on the filter in Faraday cup corresponding to the number concentration of particles. Finally, signal current is then recorded and processed by a data acquisition system (Intra and Tippayawong, 2008). The particle number concentration, C_p , is related to the signal current, I_p , at Faraday cup electrometer is given by

$$C_p = \frac{I_p}{peQ_a}, \quad (10)$$

where p is the number of elementary charge units, e is the elementary unit of charge (1.6×10^{-19} C), and Q_a is the volumetric aerosol sampling flow rate into a Faraday cup. To reduce errors due to time variations in the upstream aerosol concentrations,

repeat measurements were commenced at least 5 min after the introduction of the aerosol into the measurement system.

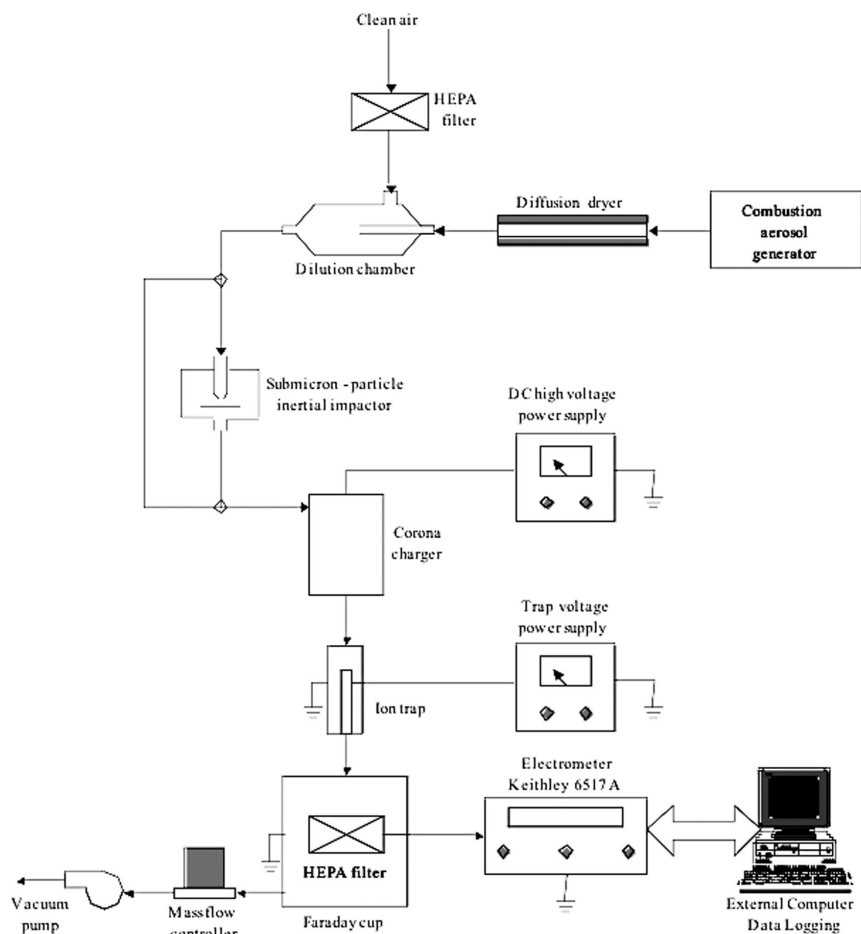


Figure 3. A schematic diagram of the preliminary experimental setup used to investigate the collection efficiency and the deposited particles inside the impactor.

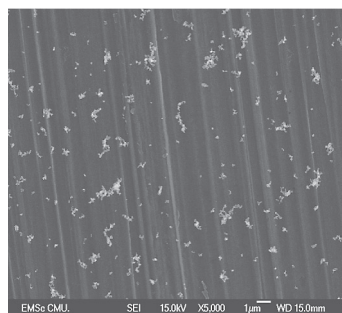


Figure 4. Scanning electron micrograph of sampling particle from the generator.

RESULTS AND DISCUSSION

The following parameters affecting the cut-off diameter were theoretically investigated in this study: the aerosol flow rate, acceleration nozzle-to-impaction plate distance and acceleration nozzle diameter. These calculations were carried out at varying aerosol flow rates between 1.0 to 5.0 l/min. An operating pressure was set at 1 bar. The acceleration nozzle diameter was varied from 0.5 to 2 mm. Figure 5 shows variation of theoretical impactor efficiency curves as a function of particle size at aerosol flow rates of 1, 2, 3, 4 and 5 l/min with the acceleration nozzle diameter of 1.0 mm. Calculations have been performed for particle size range from 10 nm to 10 μ m. It was found that the cut-off diameter decreased as the flow rate increased. With respect to the influence of the aerosol flow rate on the performance of the size selective inlet, the cut-off diameter corresponding to 1 and 5 l/min were 1.28 and 0.53 μ m, respectively. It is natural that both throat velocities and collection efficiencies increase as aerosol flow rates increase due to increased inertia. Thus, the impactor collection efficiency depends on aerosol flow rate, as shown in Figure 5. It is apparent that the collection efficiency increases between the aerosol flow rates of 1 and 5 l/min, because the inertial force acting on the particles is greater at the higher flow rate.

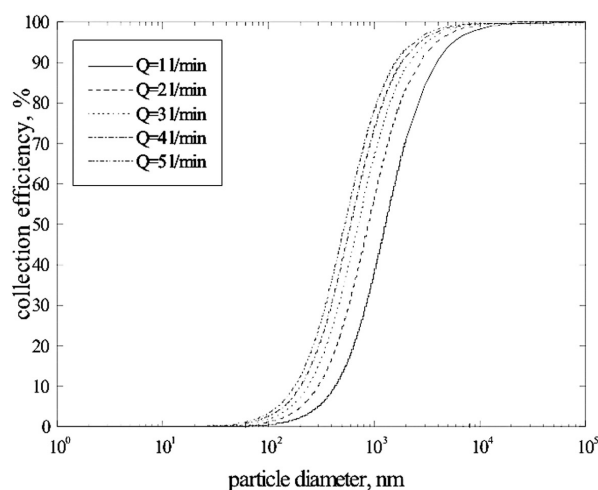


Figure 5. Variation of impactor collection efficiency with particle diameter at different operating aerosol flow rates.

For the study of the effect of the ratios of the acceleration nozzle diameter (D) to impaction plate distance (S) on the efficiency curve, Marple and Willeke (1976) showed that the 50% cut-off size $\sqrt{Stk_{50}}$ was strongly dependent upon S/D for $S/D < 1$ for rectangular impactors and for $S/D < 1/2$ for round impactors. For S/D ratios larger than these values, $\sqrt{Stk_{50}}$ and the shape of the efficiency curves are relatively constant. As design criteria, the values of S/D should be the minimum nozzle-to-plate distance used. Figure 6 shows variation of theoretical impactor efficiency curves as a function of acceleration nozzle diameter of 0.5, 1, 1.5, and 2

mm with the aerosol flow rate of 1.0 l/min, and operating pressure of 1 bar. It was found that the collection efficiency of impactor decreased when acceleration nozzle diameter decreased.

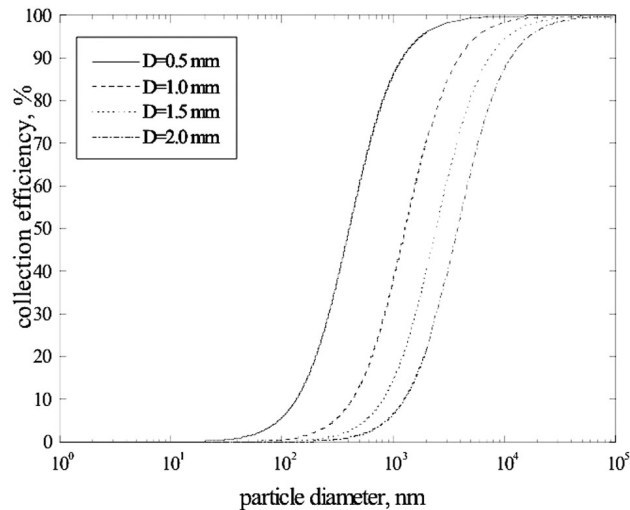


Figure 6. Variation of impactor collection efficiency with particle deameter at different acceleration nozzle diameters.

Figure 7 shows variation of measured particle number concentration and current with aerosol flow rates of both upstream and downstream of the impactor. As shown in Figure 7, the measured particle current and concentration, particle number concentration is derived from the current by using Equation 10, of both upstream and downstream was in the range from 1.5×10^{-10} to 9×10^{-9} A and 3×10^{13} to 3×10^{13} particles/m³, respectively. It was shown that the particle currents of both upstream and downstream of the impactor increased with increasing aerosol flow rate. In the same way, the particle number concentrations of both upstream and downstream increased slightly with increasing aerosol flow rate. It was also evident that the upstream particle number concentrations and currents of the impactor were slightly higher than downstream. Variation of measured particle penetration through the impactor with aerosol flow rates is shown in Figure 8. It was shown the measured particle penetration through the impactor was about 89, 56, 72 and 79% for aerosol flow rates of 1, 2, 3 and 4 l/min, respectively. It can be seen that the particle penetration through the impactor is slightly high. This was expected because all particles captured on the Faraday cup are assumed to be singly charged ($p = 1$), data reduction is required. Thus, detailed reasons of this problem should be theoretically and experimentally discussed further.

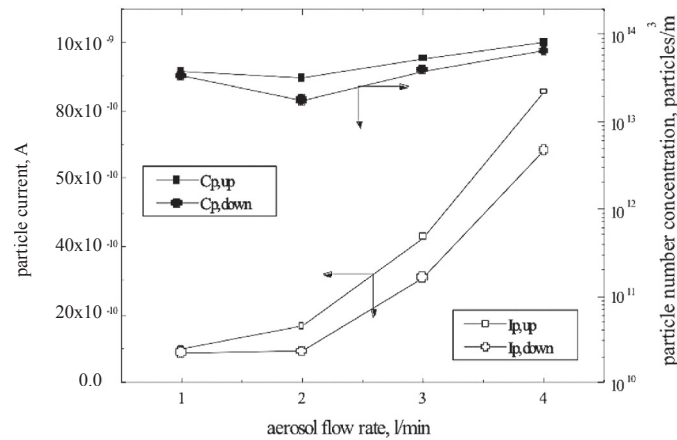


Figure 7. Variation of measured particle number concentration and current with aerosol flow rates of both upstream and ownstream of the impactor.

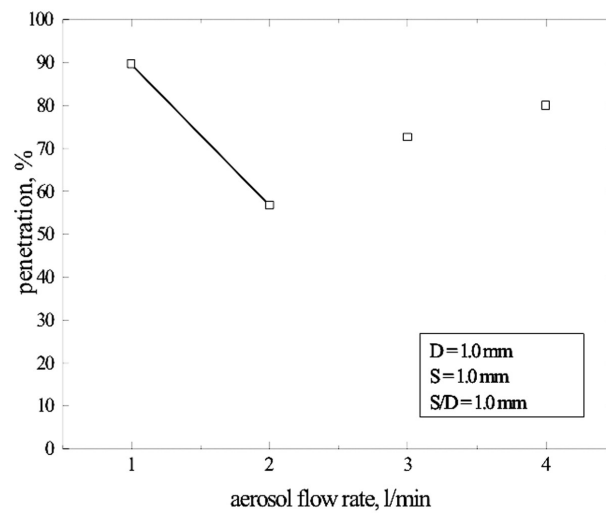


Figure 8. Variation of measured particle penetration through the impactor with aerosol flow rates.

The photograph of typical particles collected on the surface of the impaction plate inside of the impactor with sampling aerosol flow rate of 2 l/min for 30 minutes is shown in Figure 9. They were found to be agglomerated on the impaction plate. It was found inherent problems which were particle bounce and re-entrainment. The various problems in impactor use, such as the problem of particle bounce and re-entrainment, interstage wall losses and non-ideal collection characteristics of the impaction surface has been widely reported (Marple and Willeke, 1976). Particle bounce can be a severe problem in high velocity.

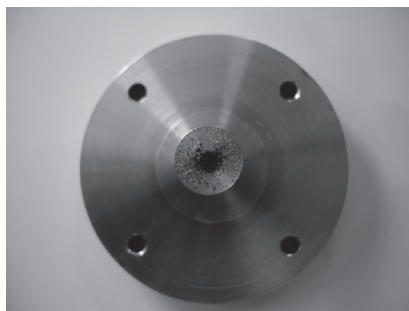


Figure 9. Photograph of typical particles collected on the impaction surface inside of the impactor.

CONCLUSION AND FUTURE WORK

The submicron-particle inertial impactor for size selective inlet of the electrical mobility particle sizing instruments has been designed, constructed and investigated. The design of the inertial impactor was based on the inertial impactor configuration of Marple and Willeke (1976). The effects of major design parameters on the cut-off diameter were analytically investigated, they were the aerosol flow rate, acceleration nozzle-to-impaction plate distance, and acceleration nozzle diameter. The impactor was preliminarily tested experimentally to observe the deposited particles on the surface of the impaction plate inside the impactor. The combustion aerosol generator was used to generate a polydisperse carbonaceous diffusion flame aerosol in the size range of approximately 10 nm – 10 μ m for this experiment. It was shown that the theoretical 50% cut-off diameter decreased as the flow rate increased and also decreased when acceleration nozzle diameter decreased. Finally, the results of the preliminary experimental tests and the photograph of typical particles collected on the surface of the impaction plate inside of the impactor was also shown and observed. Results obtained were very promising and was also found particles agglomerated on the impaction plate.

Therefore, future ongoing research will experiment on the effects of the design parameters on the impactor performance. The particle penetration efficiency of the impactor, particle size distribution both upstream and downstream of the impactor should be further theoretically and experimentally studied. One of the principal limitations of the inertial impaction method is that a significant fraction of the particles greater than the cut-point diameter (50% is from particle larger than the cut-point) that pass through the impactor contributed to multiple-charged aerosols. Therefore, further research should be also focused on this effect.

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