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Technical note

Development of a novel aerosol impactor utilizing inward flow from a ring-shaped nozzle

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ABSTRACT

This study demonstrated the proof of the concept of a novel in-line real impactor with a ring-shaped nozzle for pre-separation of 16.4 μm particles in the aerodynamic diameter in ambient inlets with a flow rate of 1500 L/min. The design parameters of the impactor were selected considering the Stk_{50} for an impactor with a rectangular nozzle. The agreement of the numerical predictions with the experimental data in terms of collection efficiency supported our simulation approach to investigate the performance of the impactor with a ring-shaped nozzle in a turbulent flow regime. Furthermore, it was shown that the collection efficiency of our newly developed impactor can be improved by using an orifice between the inlet and the nozzle of the impactor through numerical predictions and experiments. The collection efficiency curve and Stk_{50} of an impactor with an orifice becomes respectively steeper and smaller than an impactor without an orifice.

1. Introduction

Inertial impactors have been used for a variety of purposes such as sampling size selected particles (Lee & Kim, 2002), sampling and analyzing indoor and outdoor aerosol particles, and sampling bioaerosol particles (McFarland, Hu, Baehl, Richardson, & Poeschl, 2011). An inertial impactor is mainly divided into two sections, a nozzle and a collection surface. The aerosol particles are accelerated through the nozzle and then impacted on the collection surface by inertial force. The theory for the inertial impactor was well-established by Marple, Liu, and Whitby (1974) and Rader and Marple (1985). Inertial impactors have the advantage of simplicity in the sampler design but a disadvantage of generating solid particle bounce in dusty places (Markowski, 1984).

Many studies have dealt with improving the collection efficiency of inertial impactors. Grinshpun et al. (2005) obtained higher collection efficiency by making the ratio of nozzle to plate distance to nozzle diameter smaller than 1. Lee and Kim (2002) used thermophoretic force by cooling a collection surface to increase the collection efficiency by about 20%. Vinchurkar, Longest, and Peart (2009) showed that applying electrophoretic force to charged aerosol particles can increase the collection efficiency of a multi-stage impactor especially for small particles. Kim and Yook (2011) designed the impactor with an elliptical concave shaped collection surface. They found that there exists an optimum range of the ratio of major axis length to minor axis length in order to reduce the cut-off diameter of Particulate Matter (PM) 10 and 2.5 inertial impactors and showed that the

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cut-off diameters were estimated to be reduced from 10 to 6.5 μm and from 2.5 to 1.6 μm, respectively. Kim, Yook, and Ahn (2013) employed the impaction plate with an elliptical concave groove to enhance the collection efficiency of the slit nozzle inertial impactor. The square root of the Stk_{50} which is the Stokes number at 50% deposition was decreased from 0.77 to approximately 0.6. Kim, Kim, Lee, and Yook (2014) used a round-nozzle with horizontal annular inlet to reduce the cut-off diameter. The square root of Stk_{50} was decreased from 0.49 to 0.32, or 0.33 when considering the effect of gravity.

Real impactors can be used as a pre-separator for the inlet of post-sampling systems. The post-sampling systems such as wet cyclones are required to have high volume throughput in order to increase the concentration of a hydrosol significantly when the cyclone takes in aerosol at a high flow rate and delivers the particles as a hydrosol (McFarland et al., 2011). The inlet of the wet cyclone functions to remove undesirable large particles which can degrade the performance of the wet cyclone. Previously, few studies have dealt with the development of high air flow inertial impactors which have high volume throughput and the compactness required to connect them to post-sampling systems such as wet cyclones (McFarland et al., 2011). But, most inertial impactors cannot be conveniently connected to the post-sampling systems.

To address this difficulty, McFarland et al. (2011) designed an in-line real impactor as a pre-separator which can be directly connected to a wet cyclone. The accelerated flow leaving the acceleration nozzle is directed toward a punctured disk (the flat surface between two concentric circles) collection surface on the bottom of a tube. The flow then travels inward and is discharged axially through the center region of the punctured disk. For this reason, the diameter of the real impactor should be larger than the outer diameter of a wet cyclone to which the real impactor is connected.

In the present study, we designed a novel real impactor with an inlet flow rate of 1500 L/min and a cut-off aerodynamic diameter of 16.4 μm, which can be directly connected to a post-system. Unlike McFarland et al.'s (2011) in-line real impactor, our impactor was designed to have the outer diameter equal to the outer diameter of a wet cyclone in order to make a compact bioaerosol sampling system even for a high flow rate.

We related the design parameters of the impactor to two dimensionless numbers which are the Stokes number (Stk) and the Reynolds number (Re). We numerically investigated the effect of the design parameters on the collection efficiency of the impactor and compared the results with experimental data. Furthermore, we tested and compared the impactor without and with an orifice before the nozzle. We investigated both numerically and experimentally the effect of the orifice on the collection efficiency and wall loss of our newly developed impactor.

2. Design parameters of the ring-shaped impactor

Fig. 1(a) shows the structure of the real impactor with a ring-shaped nozzle. The aerosol flow is accelerated toward the center region of the impactor between two horizontal disks. Then, the flow is perpendicularly curved before the collection surface of the impactor. Thus, large particles can be collected on the collection surface. Here, M is the length of collection surface, S with a value of 16 mm is the distance between the nozzle and the plate, W is the slot width of the nozzle, and D_i is the inner diameter of the impactor. Fig. 1(b) shows a three-dimensional front view of the ring-shaped nozzle and a top view of the impactor with a circular shape. Dimensionless numbers that affect the performance of an impactor are the Stokes number (Stk) and the Reynolds number (Re) based on slot width (W) and velocity (U). As Hinds (1999) explained, Stk and Re are defined as

$$Stk = \frac{C_c \rho_p Q d_p^2}{18 \mu W^2 L}, \tag{1}$$

$$Re = \frac{\rho_a U D_c}{\mu}, \tag{2}$$

where C_c is slip correction factor, ρ_p is particle density, Q is flow rate, d_p is particle diameter, μ is viscosity of air, L is length of the ring-shaped nozzle, ρ_a is air density, and D_c is characteristic diameter of the nozzle. L is equal to π times D_i. The Stokes number that gives 50% collection efficiency (Stk_{50}) for a rectangular nozzle is equal to 0.59 (Hinds, 1999). We used the values of Stk_{50} for a rectangular nozzle for the design of our impactor since the ring-shaped nozzle looks like a rectangle when it is spread. In the present study, using Eq. (1) with Stk_{50} equal to 0.59, W can be determined as 13.8 mm for these given conditions: the cut-off aerodynamic diameter (d_{50}) of 16.4 μm, Q=1500 L/min, and D_i=58.7 mm.

Fig. 2(a) and (b) show the impactor inlet without and with an orifice, respectively. In Fig. 2(b), W_o is width of the orifice nozzle and D is the distance between the orifice nozzle and the impactor nozzle. In both designs, the flow is accelerated on the axial direction toward the collection surface. Especially for the case of an impactor with an orifice, one can expect that the flow can be more accelerated on the axial direction through a converging orifice and be more focused toward the collection surface, resulting in higher collection efficiency of particles, but the pressure drop can be larger compared to the case of an impactor without an orifice.

3. Numerical methods

We used commercial Computational Fluid Dynamics (CFD) code FLUENT 15.0 solver (2-d, steady-state and k–ε turbulent model, gravitational force) to obtain the flow field and particle trajectories inside the impactor. For the near-wall treatment, scalable wall function was used. The purpose of scalable wall functions is to force the usage of the log law in conjunction with