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Development and laboratory evaluation of a compact swirling aerosol sampler (SAS) for collection of atmospheric bioaerosols

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ABSTRACT

Inhalation of infectious bioaerosols has been linked to a variety of respiratory diseases. However, efficient sampling techniques to allow high temporal resolution sampling are limited to collect and study bioaerosols in the various occupational and ambient micro–environmental atmospheres. This study introduces a medium flow swirling bioaerosol sampler (SAS) approach that collects atmospheric bioaerosols at the flow rate of 167 Lpm (10 cubic meter per hour). The collection of bioaerosols is achieved through a combination of impaction and cyclonic centrifugal motion. Aerosol deposition efficiency tests were performed with monodispersive polystyrene latex (PSL) particles ranging from 0.1 to 10 µm. Results have shown that the sampler has cut–off size of 0.7 µm and 1.5 µm, with and without the assistance of added water vapor, respectively. The bioaerosol collection and viability tests were performed with comparison to the commercially–available BioSampler, and the results show that the collection efficiency of the SAS is 97% at the designed flow rate, while the higher flow of the new system yields more than 13 times of the collection rate compared to the BioSampler. The high collection efficiency and observed viability preservation of the SAS make it an attractive alternative for high time resolution bioaerosol sampling for atmospheric, occupational and indoor air quality monitoring.

Keywords: *Bioaerosol, sampler, impaction and centrifugal motion*

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1. Introduction

Exposure to both infectious and non–infectious bioaerosols has been reported to be associated with various respiratory and other health impacts in a variety of residential and occupational environments (Jacobs, 1994; Popendorf et al., 1996). Public awareness about the adverse health effects of bioaerosols has increased since the outbreaks of swine flu, severe acute respiratory syndrome (SARS) and avian flu (Oh et al., 2010). Bioaerosol particles have relatively low number concentrations in ambient air and their small sizes make them difficult to capture for study and identification. Thus, understanding bioaerosols to allow identification and control of their adverse health effects requires development of better sampling techniques with higher collection rates.

There are different methods for bioaerosol sampling, including impactors, impingers and filtration (Reponen et al., 1998; Li et al., 1999). Impactors are among the most widely used sampler types, due to their ability to directly collect infectious agents on the agar plate for incubation. However, impaction processes may induce structural damage to microorganisms, resulting in underestimation of exposure (Park et al., 2011). Bioaerosols are also commonly collected with impingers in which the inertial impaction and diffusion of particles into the liquid collection medium are the major mechanism for collection (Lin et al., 2000; Miljevic et al., 2009). Collected liquid samples can be diluted, thus sampling with impingers is especially suitable for heavily contaminated air. Nevertheless, the recovery of particles by liquid collection can be affected by operational parameters such as sampling duration and type of sampler (Chang and Chou, 2011). Also, the bubbling of liquid produced from the airflow transforms the already collected particles to an aerosol phase that easily escapes from sampler, thus reducing overall collection efficiency (Lin et al., 1997). Filter sampling is a conventional technique of aerosol collection for toxicological and chemical studies. However, the processing and storage of filters before analysis may affect collected sample viability in bioaerosol sampling (Henningson and Ahlberg, 1994). Different types of samplers have been developed to overcome the limitations of previous systems, such as the 3–nozzle swirling aerosol collector which collects particles at 12.5 Lpm flow rate by combining impaction and centrifugal motion, called the SKC BioSampler (Willeke et al., 1998). Roux et al. (2013) reported the design of an electrostatic sampler to concentrate biosample for more efficient collection. McFarland et al. (2010) designed a high flow rate sampler of 1 250 L/min with wetted cyclone. Because of the low ambient concentration of bioaerosols, samplers need to process large volume of air for efficient monitoring while size of sampler is also important consideration for convenient field deployment. King et al. (2009) developed the batch–type wetted wall bioaerosol sampler, however long term operation (>8 hours) decreases the collection efficiency of 1 µm bioaerosols down to 10% only. The cyclone–based aerosol sampler (Sigaev et al., 2006; Tolchinsky et al., 2010) was developed with recirculating liquid film. It has collection efficiency of only 7–30% for 500 nm bioaerosols.

We introduce a new sampler design that integrates the advantages of different particle collection mechanisms: medium flow impaction and cyclonic centrifugal motion. The sampler has 4 tapered nozzles at an angle directed towards the collector's walls. The airstream carrying particles passes through the nozzles at high speed and impacts on the surface wall of the collector, followed by flowing into a cone shape bottom and forming a swirling flow for cyclonic impaction enhancement. The centrifugal motion may help to reduce particle bounce from the impaction surface, and also it lessens the impact force of the microorganisms laden air onto the walls. So the combined effect of impaction and centrifugal motion is the increased collection efficiency and sample viability. In this method, the collection can be further facilitated by mixing the incoming aerosol with water vapor and continuously moisturizing the sampler wall to improve the collection. We describe the prototype design and demonstrated the size dependent efficiency of the sampler, as well as the preservation efficiency of bioaerosol viability compared with BioSampler.

2. Experimental Approach

2.1. Design of the medium flow Swirling Aerosol Sampler (SAS)

The objective of the present study is to design, construct and evaluate a medium flow sampler for bioaerosol collection. We considered the design criteria including compact size and easy operation for field deployment, equivalent or higher bioaerosol collection efficiency than the commercially available SKC BioSampler but with increased flow up to 10 m^3/h. Figure 1 shows the design diagram of the sampler with a view from the top (Figure 1a) and side (Figure 1b). The prototype of the sampler body was constructed using polycarbonate material. The sample air flow enters the sampler through 4 nozzles with tapered tips made of polyethylene material, which are mounted at the top of the sampler at 90° equal spacing. The air leaves the sampler through a stainless steel tubing (3/8" O.D.) in the center and connects to a vacuum pump. Each of the four nozzles is aligned at an angle α to the horizontal tangent at an intersection point of the nozzle axis with an inner surface and angle β to the vertical axis of the sampler. The total flow rate through SAS is 167 Lpm (10 m^3/h), α=60° and β=30°. Both angles were optimized and determined empirically based on the formation of swirling flow inside sampler and resulting collection efficiency. Only the results of these optimized angles are shown in the study. The total height of the sampler is 200 mm with an inner cylindrical diameter of 50.0 mm; the height of cone is 50.0 mm; distance between the nozzle bottom and cone top is 50.0 mm; distance between the center of the nozzle outlet and cylinder wall is 3 mm. The lower part of sampler has a smaller cone shape with half the size of larger cone shape. Initial design didn't include the small cone shape, but it resulted in high evaporation rate for collection liquid. Thus the small cone shape was added so that the collection liquid can be trapped to reduce evaporation. The tapered nozzle has an outlet tip diameter of 3.0 mm to realize an ideal impaction cut–off diameter of 1.5 µm following the classic impaction theory:

$$St_{50} = \frac{\rho_p C_c d_{50}^2 U}{9 \mu W} \quad (1)$$

where, ρ_p is the particle density assumed as 1.2 g/cm^3, d_{50} is the particle diameter, C_c is the Cunningham slip factor, U is the mean jet velocity and μ is the air viscosity as 1.8×10^{-5} Pa s, while W is the jet diameter.

The air that passes through the nozzle tips accelerates aerosols then impacts on the wall of the cylinder followed by a swirling flow, as exhibited by the dashed line in Figure 1b, to realize combined effects of impaction and centrifugal motion. The use of multiple nozzles for medium flow rate sampling yields a pressure drop through the sampler of 20 kPa at 167 Lpm.

2.2. The PSL experimental setup

Figure 2 shows the experimental setup diagram for the size dependent collection efficiency of the sampler by using mono-dispersive polystyrene latex (PSL, Fluoro–max, Thermo Scientific) particles covering the size range from 0.1 µm to 10 µm (e.g., 0.1 µm, 0.5 µm, 1 µm, 2 µm, 5 µm, 10 µm). Two configurations were tested with and without the vapor assistance as shown in Figure 2. For the dry aerosol collection efficiency test, additional backup filter connected at downstream of the sampler to inspect the penetration efficiency. Each test lasted for 30 minutes and three repeated tests were carried out (for reproducibility). The vapor was generated in a sealed stainless steel chamber with a PID–controlled heater sitting underneath. The chamber was loaded with Milli–Q water and a mild temperature of 30 °C was set to generate the vapor while incoming air remained at 25 °C. Aerosol laden air passed through the chamber mixing with the vapor and humidified up to 95% relative humidity as measured by Vaisala HMP60 probe. PSL particles were generated by a six–jet collision nebulizer (BGI CN25, BGI Inc., Waltham MA) and passed through a mixing chamber in which they are neutralized by an array of 4 ionizers (Staticmaster Ionizers 2U500, Amstat, Glenview, IL) to remove the particle static charges, followed by drying and dilution by particle–free air filtered using a HEPA (High Efficiency Particulate Air) filter. The outlet air humidity was measured by the Vaisala HMP60 probe and remained relatively consistent as room condition of 45% in the

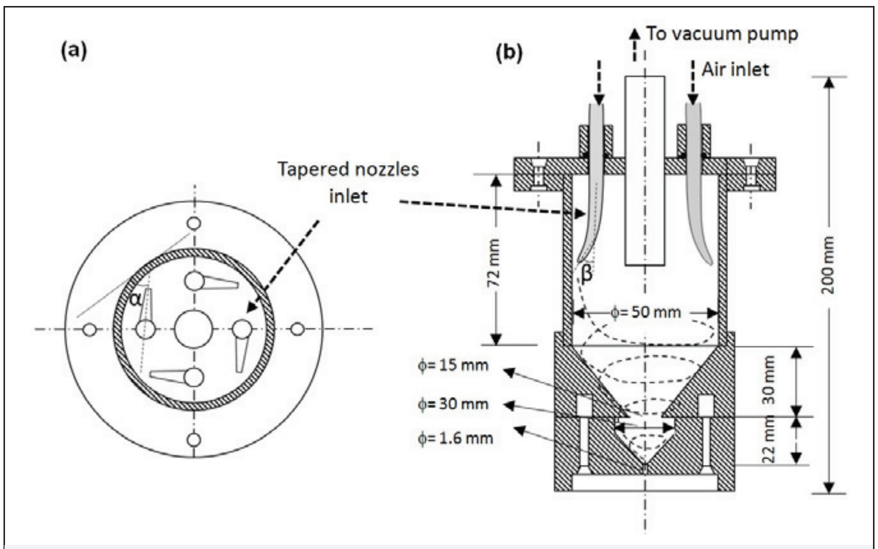

Figure 1. *Schematic diagram of the Swirling Aerosol Sampler (SAS): **(a)** top view; **(b)** side view.*