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Improving the collection efficiency of the liquid impinger for ultrafine particles and viral aerosols by applying granular bed filtration

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ABSTRACT

Liquid impingers are utilized to collect bioaerosols for many advantages, such as avoiding dehydration of biological agents. However, many previous studies have reported that the liquid impingers are surprisingly inefficient for the collection of ultrafine bioaerosols, with collection efficiencies $< 30\%$. In the present work, we have successfully improved the collection efficiency of the liquid impinger (AGI30) to as high as 99% for particles in the size range of 20–400 nm with the aid of packed glass beads. We also systematically investigated the effects of influential factors on the collection efficiency. These factors include the volume of the sampling liquid (0, 20 and 30 mL), depth (0, 7 and 10 cm) of packed glass beads and sampling flow rate (4, 6 and 8 liter per min, lpm). According to our experimental results, increasing the depth of packed glass beads and the volume of sampling liquid can enhance the collection efficiency. Also, decreasing the sampling flow rate can increase the collection efficiency and reduce the loss of sampling liquid. For the sampling of viable MS2 phages, the collection efficiency of AGI30 sampler with packed glass beads is much higher than that without packed glass beads. Conclusively, this study validates that the granular bed filtration can enhance the collection efficiency of liquid impingers for submicron and ultrafine particles and viral aerosols.

1. Introduction

Various types of liquid impinger have been utilized for aerosol sampling since the first case, the Greenburg–Smith impinger, was invented in 1922 (Marple, 2004). Using liquid impingers is a suitable method for sampling bioaerosols as compared with some other common methods such as filtration, which needs to separate the bioaerosols from the filter for further assays (Verreault, Moineau, & Duchaine, 2008). Furthermore, collecting bioaerosols in a liquid impinger can help avoid dehydration of biological samples, and the all-glass impinger (AGI) and SKC BioSampler are particularly designed to collect bioaerosols.

The virus particles such as SARS and MERS coronavirus (80–200 nm) are submicron and ultrafine particles, and ultrafine bioaerosols can penetrate deeply into the pulmonary tract and may cause serious health effects (Graham, Donaldson, & Baric, 2013; Lin et al., 2004). Lindsley et al. (2012) demonstrated that influenza patients generate smaller and more aerosol particles than healthy subjects (Yang, Lee, Chen, Wu, & Yu, 2007). However, most previous studies regarding collection efficiency of liquid

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impingers for bioaerosols focus on the micrometer-sized bioaerosols (Tseng & Li, 2005). Up to the present time, there are only a few studies on the collection efficiencies of liquid impingers for submicron viral aerosols, and ultrafine particles (Hogan et al., 2005; Miljevic, Modini, Bottle, & Ristovski, 2009; Spanne, Grzybowski, & Bohgard, 1999; Wei, Rosario, & Montoya, 2010). Spanne et al. (1999) found that the collection efficiency of an AGI for particles with diameters between 0.02 and 0.7 μm was less than 20%. Wei et al. (2010) discovered that the midget impinger's collection efficiency for particles in the range of 30–100 nm was less than 20%. Hogan et al. (2005) also found that the collection efficiencies of the AGI30 sampler were surprisingly low ($<10\%$) for sampling virus particles with sizes of 30–100 nm. The SKC BioSampler, which applies the combination of impaction and centrifugal motion for collecting airborne particles (more efficient for larger particles), has also been proven to be an inefficient sampler for particles smaller than 0.3 μm (Hogan et al., 2005; Willeke, Lin, & Grinshpun, 1998). Therefore, to improve the collection efficiency of the liquid impingers for submicron viral aerosols, we can utilize the Brownian diffusional deposition of the ultrafine particles. Miljevic et al. (2009) studied the efficiency of an impinger with fritted nozzle tip for collecting ultrafine particles. They obtained a significantly high collection efficiency (~95%), primarily because of the diffusional deposition of particles in the fritted nozzle tip, particularly in the case of finer porosity frits. However, it is difficult to harvest the biological agents from the porous fritted nozzle tip. Numerous previous studies have reported the excellent removal efficiency of granular bed filtration for ultrafine particles (Bémer, Subra, Morele, Charvet, & Thomas, 2013), and thus, this technique seems to be a practical scheme for improving the collection efficiency of liquid impinger for submicron and ultrafine bioaerosols. To increase the recovery of the collected biological agents from the granular bed, the packed material used should be spherical with a smooth surface. Thus, in this study, we intended to enhance the collection efficiency of the liquid-based impinger for ultrafine particles and viral aerosols with the aid of packed glass beads. We selected the AGI30 sampler to test our approach because the configuration of this sampler is suitable for packed glass beads. The influential factors on the collection efficiency, including the volume of the sampling liquid, the depth of packed glass beads, as well as the sampling flow rate, were systematically studied. We found that the application of packed glass beads significantly improved the collection efficiency of AGI30 sampler for ultrafine particles and viral aerosols. Thus, our proposal that the granular bed filtration can enhance the collection efficiency of liquid impingers for ultrafine particles and bioaerosols was proven to be valid.

2. Methodology

2.1. Collection efficiency for submicron particles

The experiments of the impinger's collection efficiency for submicron particles were conducted in the experimental system demonstrated in Fig. 1. The zero air supply system provides dry clean air for the experimental system. This air supply system contains an oil-free air compressor (ORSO JET, Model No. AMP5125), a homemade diffusion dryer, a home-produced active carbon cartridge, and a High-Efficiency Particulate Air (HEPA) filter (HEPA capsule, Part Number 12144, PALL Corporation, USA). A Collison-type constant output atomizer (Model 3076, TSI Inc., USA) was employed to generate droplets from the solution or suspension containing the test materials. In the Set 1 experiment, LB liquid medium (LB Broth, Difco™) was utilized to produce the test aerosol particles because the LB medium was employed to culture the test bioaerosols (MS2 phages). These droplets transformed to neutralized submicron particles after passing through the homemade diffusion dryer and then a Kr-85 radioactive Aerosol Neutralizer (Model 3077, TSI Inc., USA). The homemade diffusion dryer was used to dry and remove water from aerosol produced by the atomizer. In the dryer, the aerosol flows through a channel (60 cm long and 1 cm in diameter) surrounded by silica gel desiccant to remove extra wetness by diffusional capture.

A switch valve after the Kr-85 Aerosol Neutralizer served to switch the aerosol flow path: (1) passing through the sampler (2) or not through the sampler. The sampler used in the experiments was an All-Glass Impinger (AGI30, ACE GLASS Inc. Vineland, NJ., USA) and the sampling liquid in the AGI30 was sterilized distilled water. A diffusion dryer was used to remove excess moisture and water droplets generated from the AGI30. We measured the number concentration and size distribution of the test aerosol particles after passing through the sampler or not through the sampler by using the Scanning Mobility Particle Sizer (SMPS™ = DMA + UCPC, Model 3936L76, TSI Inc., USA). We used the following equation to evaluate the collection efficiency (E_{dp} based on number concentration) of the sampler for the aerosol particles of diameter d_p:

$$E_{dp}(\%) = \left(1 - \frac{N_{dp,out}}{N_{dp,in}}\right) \times 100\% \quad (1)$$

in which, $N_{dp,out}$ is the number concentration of particle of diameter d_p after passing through the sampler [route (1)]; $N_{dp,in}$ is the number concentration of particle of diameter d_p not through the sampler [route (2)].

In this study, the AGI30 sampler was packed with glass beads (Fig. 1(b)) to enhance its collection efficiency for ultrafine particles. To avoid the ultrafine particles attaching to the glass beads, we selected the glass beads with smooth surfaces as shown in Fig. 1(c). For comparison, the experiments of AGI30 sampler without packed glass beads were also conducted.

In the Set 1 experiment, we investigated the effects of some influential factors on the collection efficiency of the sampler. These influential factors included the sampling flow rate (4, 6 and 8 lpm), the depth of packed glass beads (0, 7 and 10 cm), and the volume of sampling liquid in the sampler (0, 20 and 30 mL). In our experimental setting, the levels of 20-mL and 30-mL sampling liquid were the same as the 7-cm and 10-cm depth of the packed glass beads, respectively. Table 1 summarizes the parameter