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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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A R T I C L E   I N F O

Article history:
Received 14 January 2016
Received in revised form
11 May 2016
Accepted 10 August 2016
Available online 16 August 2016

Keywords:
Liquid impingers
Ultrafine particles
Bioaerosols
Granular bed filtration

A B S T R A C T

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.

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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...
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 a 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, DifcoTM, USA) 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, 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:

\[ E_{dp} (%) = \left( 1 - \frac{N_{dp, out}}{N_{dp, in}} \right) \times 100\% \] (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
Table 1
Summary of parameter values used in the experiments.

| Parameters                        | Condition                                                                 |
|-----------------------------------|---------------------------------------------------------------------------|
| Test particles                    | Luria–Bertani aerosol particles (LB particle), MS2 bacteriophage aerosol particles (MS2 particle) |
| diameter of test particles, \(d_p\) | 16–450 nm                                                                 |
| Fluid absolute temperature, \(T\) | 298 K                                                                     |
| Porosity, \(\varepsilon\)         | 0.367                                                                     |
| Glass beads diameter (mm), \(d_g\) | 3                                                                         |
| The glass beads packed depth (cm), \(h\) | 0, 7, and 10                                                             |
| Volume of sampling liquid in the impinger (mL), \(V_s\) | 0, 20, and 30                                                            |
| Sampling flow rate through impinger (liter per min, lpm), \(Q_s\) | 4, 6, and 8                                                               |
| Example of the AGI30 sampler setting: \(10h\ 30V_s\) 4Q_s | AGI30 is packed with 3-mm glass beads; packed depth is 10 cm; volume of sampling liquid is 30 mL; sampling flow rate is 4 lpm. |

Fig. 1. (a) Diagram of experimental system, (b) AGI30 with packed glass beads, and (c) images for the glass beads used to pack the AGI30 sampler.
values used in the experiments. To verify our experimental data were stable and reliable, each experiment was triplicate, and the coefficients of variation of the experimental data reported in this study were less than 10%.

In this study, we used a criterion, the “sampler quality”, to evaluate the samplers. The sampler quality for the aerosol particles of diameter $d_p (qS_{dp})$ is expressed as the following equation:

$$qS_{dp} = \ln \left[ 1 / (1 - E_{dp}) \right] / \Delta p = \ln (1 / P) / \Delta p$$  \hspace{1cm} (2)

in which, $\Delta p$ is the pressure drop of the sampler; $P$ is the particle penetration. This criterion is originally used for evaluating filter media performance and known as “filter quality factor” (Hinds, 1999; Huang et al., 2013).

2.2. Collection efficiency for viral aerosols

In the Set 2 experimental system, the collection of viral aerosols (MS2 phage) by using the AGI30 sampler was evaluated. Similar to the Set 1 experimental system, the Set 2 system used MS2 phage suspension as a replacement of the LB media to produce the test aerosol particles. The MS2 phage has a diameter of around 27 nm (Strauss & Sinsheimer, 1963). Our previous study described the same procedure for the preparation of phage suspension (Yu, Lee, Lin, & Huang, 2008). Each experiment in Set 2 was also triplicate. The numbers of viable MS2 phage collected in the AGI30 sampler were determined by enumerating the plaque-forming unit (PFU) in the double-layered cultures, respectively. We used the following equation to evaluate the overall collection efficiency of the sampler for viable phages ($E_{PFU}$):

$$E_{PFU} = \frac{PFU_{s} \times V_s}{PFU_{a} \times V_a}$$ \hspace{1cm} (3)

where $PFU_{s}$ (PFU/mL) is the phage titers in the sampler at sampling time $t_s$; $V_s$ (mL) is the volume of sampling liquid; $PFU_{a}$ (PFU/mL) is the phage titer in the atomizer; $V_a$ (mL) is the volume of MS2 phage suspension in the atomizer consumed during $t_s$. $E_{PFU}$ is the total amount of viable MS2 phages captured by the sampler during the sampling time $t_s$ divided by the total amount of MS2 phages aerosolized during $t_s$. To investigate the effect of packed glass beads on the recovery of MS2 phages from the AGI30 sampler, we added the MS2 suspension (titer: $10^7$ PFU/mL) in the AGI30 sampler with and without packed glass beads and then took the MS2 samples from the AGI30 samplers with an auto pipette. The recovery of MS2 was evaluated based on PFU counting. Accordingly, the recoveries of MS2 from the AGI30 samplers with and without packed glass beads were 100.78 ± 13.13% and 93.96 ± 7.26%, respectively. The concentration of the aerosolized MS2 phage ($C_{aerosolized}$) in the system was evaluated as what follows:

$$C_{aerosolized} = \frac{PFU_{s} \times V_s}{Q_s \times t_s}$$ \hspace{1cm} (4)

in which, $t_s$ (min) is the sampling time; $PFU_{s}$ (PFU/mL) is the MS2 phage titers in the sampler at $t_s$; $V_s$ (mL) is the volume of sampling liquid; $Q_s$ (m$^3$/min) is the sampling flow rate. We defined the ratio of the logarithm of $C_{aerosolized}$ (PFU/m$^3$) to the logarithm of the MS2 phage titer (PFU/mL) in the atomizer ($PFU_{a}$) as the atomization factor ($AF$), given by the following equation (Yu et al., 2008):

$$AF = \frac{\log(C_{aerosolized})}{\log(PFU_{a})}$$ \hspace{1cm} (5)

![Fig. 2. The size distribution of aerosol particles generated from Luria–Bertani (LB) liquid medium is a lognormal distribution with a geometric mean of 100.1 nm and a geometric standard deviation of 1.962. The size distribution of MS2 bacteriophage with media is also lognormal distribution with a geometric mean of 107.3 nm and a geometric standard deviation of 1.893. When the MS2 bacteriophage with media is 3-fold diluted with sterile water, the geometric mean of the generated aerosol particles reduced to 67.83 nm and the geometric standard deviation is 2.077. The presented size distributions indicate the mean by distributions of five repeats. The coefficient of variation between each repeat was less than 5%.](image-url)
3. Results and discussion

3.1. Effect of volume of sampling liquid and depth of packed glass beads on the collection efficiency of AGI30 sampler

In this study, the aerosol particles (LB media and MS2 phage particles) used to conduct the experiments were lognormally distributed. As shown in Fig. 2, the geometric mean (GM) and geometric standard deviation (GSD) of LB media particles were 100.1 nm and 1.962 and the GM and GSD of MS2 phage with media particles were 107.5 nm and 1.893. MS2 phages have to propagate in the host cells cultured in the medium. The host cells can be removed easily by filtration, but it is difficult to separate MS2 phages from the medium. We tried to reduce the influence of medium by diluting the MS2 suspension with sterile water. After a 3-fold dilution with sterile water, the MS2 phages were aerosolized, and then the airborne particle size distribution of the MS2 phages was measured as shown in Fig. 2.

The collection efficiency of the AGI30 sampler with packed glass beads increased with the increase of sampling liquid ($V_s$). As shown in Fig. 3(a) and (b), when the $V_s$ increased from 0 to 30 mL, the minimum collection efficiency rose from 0.36 to 0.99. Several previous studies demonstrated the effect of increasing the sampling liquid on the collection efficiency of liquid impingers (Miljevic et al., 2009; Wei et al., 2010). A higher liquid volume resulted in more time for particles to interact with the collection liquid and produced a greater opportunity for a particle to be captured by the liquid via diffusion or

![Fig. 3. The aerosol particle collection efficiency ($E_{dp}$) of AGI 30 sampler with packed glass beads. (a) The sampling flow rate is 4 liter per minute (lpm) and (b) 6 lpm. The presented data indicate the means of triplicate experiments, and the coefficients of variation of the experimental data were less than 5%.](image-url)
impaction. This approach (increasing sampling liquid) could also be applied to enhance the collection efficiency of AGI30 with packed glass beads.

Both Golshahi, Abedi, and Tan (2009) and Ozis, Singh, Devinny, and Sioutas (2004) demonstrated that particle collection efficiency increased with the depth of dry granular filter media. As anticipated, it took more time for the air to pass through a thicker granular bed. Thus, there was a longer contact time for more particles to be collected by either diffusion or sedimentation or impaction. Usually, increasing the depth of packed glass beads may enhance the collection efficiency of the AGI30 samplers. However, the density and viscosity of water are much higher than the air, and thus, the behavior of the liquid impinger packed with a granular bed is a little different from that of the dry granular filter media. When the depth of packed glass beads (h) in the sampler is lower than the level of sampling liquid (L), the granular bed may become unstable during sampling owing to the turbulent fluid movement. Under this condition, the granular bed could not function well, and the capture efficiency of granular bed for particles would decrease, as the case of the settings of 7h 30V_s 4Q_s and 7h 30V_s 6Q_s shown in Fig. 3(a) and (b). However, increasing the depth of packed glass beads could help stabilize the granular bed and thus enhance the capture efficiency for particles. As shown in Fig. 3(a) and (b), the results of pair settings of 7h 30V_s 4Q_s vs. 10h 30V_s 4Q_s and 7h 30V_s 6Q_s vs. 10h 30V_s 6Q_s is a good example to demonstrate this effect.

Fig. 4. Collection efficiency of the AGI30 sampler as function of (a) particle diameter, (b) Stokes number (Stk), and (c) dimensionless deposition parameter ($\mu$). The presented data indicate the means of triplicate experiments, and the coefficients of variation of the experimental data were less than 5%.
3.2. Effect of sampling flow rate on the collection efficiency of AGI30 sampler

Fig. 4 demonstrates the effect of sampling flow rate on the collection efficiency of AGI30 sampler for the LB media particles. The AGI30 sampler had the highest collection efficiency when being operated at the lowest sampling flow rate of 4 lpm. When the sampling flow rate increased to 6 and 8 lpm, the collection efficiency reduced about 20%. These two collection efficiency curves for AGI30 at sampling flow rates of 6 lpm and 8 lpm crossed over at particle diameter of 40 nm. For capturing particles smaller than 40 nm, the 6-lpm sampling flow rate was better than 8-lpm. In contrast, the 8-lpm sampling flow rate was better than 6-lpm for collecting particles larger than 40 nm. This result was reasonable because small particles were captured mainly by the Brownian motion, which was presumably the primary collection mechanism at lower flow rates. Conversely, the larger particles were mainly collected by inertial impaction, which worked better at higher flow rates. A similar result has been reported by Hogan et al. (2005) in which MS2 and T3 phages were used as the test aerosol particles.

As shown in Fig. 4, when the AGI30 sampler was packed with 3-mm glass beads with a packed depth of 10 cm, its collection efficiency for airborne particles increased dramatically. The collection efficiency of AGI30 operated at a sampling flow rate of 8 lpm increased from 0.2–0.4 to 0.3–0.65 after packed with glass beads. When the sampling flow rate reduced to 4 and 6 lpm, the collection efficiencies of AGI30 with packed glass bead achieved as high as 0.99 for particles of 20–450 nm. Presumably, the packed glass beads enhanced the collecting of particle by either the Brownian diffusion or inertial impaction or both of them. Ozis et al. (2004) investigated the removal efficiency of granular filters packed with lava rock and sand for aerosol particles of 0.05–2.5 μm. In their experimental setting, the dominant mechanisms for collecting particle were sedimentation and diffusion. They found that the particle collection efficiency declined with the increase of flow rate. A similar result had been reported in Golshahi et al. (2009), which studied the granular filtration efficiency for airborne particles in the range of 10 nm to 15 μm.

For the AGI30 sampler, a lower flow rate results in a higher residence time, which offers more opportunities for the interaction between the particles and collectors (granules and sampling liquid). Additionally, the liquid-based samplers may lose the collected particles due to the aerosolization of the sampling liquid during sampling. Thus, the improved collection efficiency could also be attributed to the decreased aerosolization from bubbler under lower sampling flow rate (Deppert et al., 1994; Deppert & Wiedensohler, 1994; Riemenschneider et al., 2010).

Fig. 5. The sampler quality of the AGI 30 sampler with packed glass beads. The presented data indicate the means of triplicate experiments, and the coefficients of variation of the experimental data were less than 5%.
In Figs. 3 and 4(a), the observed minimum collection efficiency in many experiments is for particles of about 100 nm. This could be simply explained as the size at which the diffusion is no longer efficient while the impaction is not yet efficient. To investigate the effect of impaction and diffusion on the collection efficiency, we discussed the correlation between collection efficiency and each of the Stokes number and the dimensionless diffusional deposition parameter in the following section.

The collection efficiency of a typical impactor-type sampler is governed by the Stokes number (Friedlander, 2000; Hinds, 1999). The dimensionless Stokes number of an impactor is defined as the ratio of the particle stopping distance \( S \) at the average nozzle exit \( U_0 \) to the jet radius \( r_j \), shown in the following equation:

\[
Stk = \frac{S}{r_j} = \frac{\tau U_0}{r_j} = \frac{\rho p d_p^2 C_c U_0}{18 \eta r_j} \tag{6}
\]

in which, \( \rho_p \) (kg/m\(^3\)) is the particle density; \( d_p \) is the particle diameter; \( \eta \) is the viscosity of the air. \( C_c \) is the slip correction factor given by

\[
C_c = 1 + \frac{2 \lambda}{d_p} \left[ 1.257 + 0.4 \exp \left( -0.55 \frac{d_p}{\lambda} \right) \right] \tag{7}
\]

in which \( \lambda \) is the mean free path for air, equal to 0.066 \( \mu \)m under the standard condition (Hinds, 1999). For a typical impactor-type sampler, the shape of the collection efficiency \( (E_{\text{Stk}}) \) vs. Stokes number \( (Stk) \) curve would not change under different sampling flow rates. According to the plots of the \( E_{\text{Stk}} \) of AGI30 samplers vs. Stk, as shown in Fig. 4(b), when the sampling flow rate was comparatively low (4 and 6 lpm), the AGI30 packed with glass beads might be an impactor-type sampler and these two curves \( (E_{\text{Stk}} \text{ vs. Stk}) \) were identical. When the sampling flow rate increased from 6 to 8 lpm, the packed glass beads would transfer from fixed bed filter to fluidized bed filter, resulting in a decrease of the collection efficiency. Besides, the collection efficiency increased with Stk when Stk > 0.07, indicating impaction was the primary mechanism under this condition.
Fig. 4(c) demonstrates the collection efficiency owing to diffusion of aerosol particles to the collectors in the sampler as a function of the dimensionless diffusional deposition parameter, $\mu$, which is expressed as the following equation:

$$\mu = \frac{Dh}{Q_s} \left( \frac{kT c}{3\pi \eta d_p} \right) \times \frac{h}{Q_s}$$

(8)
where \( D \) is the particle diffusion coefficient; \( h \) is the depth of the packed glass beads; \( k \) is the Boltzmann’s constant; \( T \) is the absolute temperature. The collection efficiency \( (E_{\mu}) \) increased with the dimensionless diffusional deposition parameter, \( \mu \), as \( \mu > 10^{-7} \), implying that the Brownian diffusion dominated the collecting of particles under this condition.

We also investigated the effect of the diameter of packed glass beads (3-mm and 5-mm glass beads) on the collection efficiency of the sampler (Supplementary material, Fig. S1). For the dry granular bed, increasing the granule diameter enlarges the porosity of the granular bed and reduces the contact surface area (the porosity of the packed 3-mm and 5-mm glass beads is 0.367 and 0.398 respectively). As a result, the overall capture efficiency declined with the increase of granule diameter (Golshahi et al., 2009). However, the smaller the diameter of the packed glass beads is, the higher the pressure drop of the AGI30 sampler will be. Moreover, the higher pressure drop will make the sampler difficult to operate. According to our experiment result, the 3-mm glass beads with smooth surfaces are the optimal choice for the packed bed.

3.3. Sampler quality

Applying the packed glass beads can enhance the collection efficiency of the AGI30 sampler for aerosol particles in some settings, but it also raises the pressure drop of the sampler and creates a heavy load on the sampling pump. However, the best sampler should be the one that gives the highest collection efficiency with the least pressure drop. A useful criterion for comparing different samplers is the “sampler quality” (Eq. (2)), which is initially used for assessing the filter media performance. Because increasing sampling flow rate would increase the pressure drop of the sampler, the comparison of sampler quality has to be conducted under the same sampling flow rate. Fig. 5 (and Fig. S2) shows the sampler quality of the AGI30 samplers under different settings. The sampler setting with the highest sampler quality at the sampling flow rate of 4 and 6 lpm were “10h 30V, 4Q,” and “10h 30V, 6Q,” respectively. The superior collection efficiency of these two settings led to this result, although the highest depth of packed glass beads (10 cm) created a considerable pressure drop. However, because higher sampling flow rate would result in more loss of sampling liquid (2-mL loss at 6 lpm vs. 1-mL loss at 4 lpm), the setting of “10h 30V, 4Q” might be better than “10h 30V, 6Q.” Thus, the best performing condition for the sampler is the setting of “10h 30V, 4Q.”

3.4. Collection of MS2 phage aerosols

The Set 2 experiment investigated the collection of MS2 phage aerosols by using the AGI30 sampler, and the titers of MS2 phage in the sampling liquid are shown in Fig. 6(a). The AGI30 sampler with packed glass beads exhibited superior collection efficiency for the MS2 phages as compared with that without packed glass beads. The AGI30 sampler (without packed glass beads) has a lower but more stable collection efficiency over time. A previous study also demonstrated that AGI30 sampler had a stable collection efficiency for T3 phages (Hogan et al., 2005). However, the unstable sampling behavior of the AGI30 sampler with packed glass beads might be owing to both the improved collection efficiency (the sampling liquid’s property changed after mixing with MS2 and media aerosols) and larger sampling liquid losses (up to 5%) via evaporation concentrating the phage titer with time.

To observe more insight into the sampling behavior of the AGI30 sampler as a phage collector, we evaluated the \( E_{\text{EPFU}} \) (Eq. (3)) of the sampler as shown in Fig. 6(a). An ideal sampler is the one that has steady collection efficiency and preserves phage viability during sampling. No matter whether the AGI30 sampler was packed with glass beads or not, the \( E_{\text{EPFU}} \) was relatively stable within 20 min. The \( E_{\text{EPFU}} \) of AGI30 sampler without glass beads was still constant at 30 min, but the \( E_{\text{EPFU}} \) of AGI30 with packed glass beads increased (from 0.0068) to 0.0144. Fig. 7(a) demonstrates the collection efficiency (\( E_{\text{dp, mass}} \) is calculated from Eq. (1), in which the number concentration is replaced by the mass concentration) of AGI30 packed with glass beads increased with sampling time, which was consistent with the result of \( E_{\text{EPFU}} \). Although the collection efficiency (\( E_{\text{dp, mass}} \)) of the AGI30 sampler (without packed glass beads) fluctuated with time, as shown in Fig. 7(b), the integration of \( E_{\text{dp, mass}} \) with time agreed with the result of \( E_{\text{EPFU}} \).

The \( E_{\text{EPFU}} \) was much lower than 1.0, indicating that many viable MS2 phages lost in the piping system, as well as the diffusion dryer and the neutralizer. Therefore, we employed Eqs. (4) and (5) to estimate the concentration of aerosolized viable MS2 phages \( (C_{\text{aerosolized}}) \) and the aerosolization factor \( (AF) \) in the experimental system, respectively (Yu et al., 2008). As shown in Fig. 6(b), both \( C_{\text{aerosolized}} \) and AF based on the AGI30 sampler without packed glass beads were comparable to the result of our previous study (Yu et al., 2008). Owing to the higher collection efficiency of AGI30 sampler with packed glass beads, the \( C_{\text{aerosolized}} \) and AF based on this sampler was much higher.

The collection efficiency for MS2 phages obtained in this study is similar to that reported by Hogan et al. (2005), in which AGI30 sampler (collection efficiency: 0.01–0.018) and SKC BioSampler (collection efficiency: 0.001–0.006) served for T3 phage collection over time. Hermann et al. (2006) investigated the collection and detection of aerosolized porcine reproductive and respiratory syndrome virus (PRRSV) in air-sampling systems based on quantitative reverse transcriptase PCR (QRT-PCR). As estimated by QRT-PCR, the mean collection efficiency of PRRSV were 0.02188, 0.01585 and 0.009333 for the SKC BioSampler (12.5 lpm), AGI30 (12.5 lpm) and AGI4 (6 lpm), respectively. Because the recovery rate of viruses with PCR method is much higher than that with culture method (Liu et al., 2012), and perhaps this may be the reason why collection efficiency reported by Hermann et al. (2006) is greater than ours. Furthermore, the composition of sampling liquid and spray liquid aerosolized and relative humidity can also significantly affect the collection efficiency of liquid impinge for viral aerosols (Hermann et al., 2006; Liu et al., 2012).
4. Conclusion

In this study, we successfully improved the efficiency of AGI30 sampler for the collection ultrafine particles and viral aerosols applying packed glass beads. Moreover, we systematically investigated the effects of sampling flow rate, depth of packed glass beads as well as the volume of the sampling liquid on the collection efficiency. Increasing the sampling flow rate would reduce the collection efficiency of the sampler. On the other hand, increasing the depth of packed glass beads or volume of sampling liquid would enhance the collection efficiency. For the collecting of viable MS2 phages, the AGI30 sampler with packed glass beads performed much better than that one without packed glass beads. Conclusively, applying the AGI30 sampler with packed glass beads under an optimum setting can collect the ultrafine particles and viral aerosols with excellent efficiency.

Acknowledgment

The authors would like to thank the Ministry of Science and Technology of Taiwan for providing the financial support (Contract number MOST 100-2221-E-010-003-MY3) and Ms. Jia-yu Chen for the help of English editing.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at http://dx.doi.org/10.1016/j.jaerosci.2016.08.002.

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