

Collection characteristics of a batch-type wetted wall bioaerosol sampling cyclone

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Abstract The collection efficiency and sample retention of a batch-type wetted wall bioaerosol sampling cyclone (BWWC) were experimentally characterized. The BWWC is designed to sample air at 400 l/min and concentrate the particles into 12 ml of water. Aerosol is transported into a cylindrically-shaped axial flow cyclone through a tangential slot and the particles are impacted on the inner wall, which is wetted by air shear acting on a liquid pool at the base of the cyclone. The retention of collected particles and the aerosol collection efficiency of the BWWC were evaluated with polystyrene latex beads (PSL), sodium fluorescein/oleic acid droplets, and *Bacillus atrophaeus* (aka BG) spores. The retention of particles was determined by adding hydrosol directly into the device, running the BWWC for a pre-set period of time, and then determining the amount of particulate matter recovered relative to the initial amount. For 1- μ m diameter PSL, 90% of the particles were recoverable from the cyclone body immediately after their introduction; however, only 10% were retained in the collection liquid after 8 h of operation. The aerosol sampling efficiency was determined by comparing the amount of particulate

matter collected in the liquid with that collected by a reference filter. The collection efficiency was 50–60% for 1- and 3- μ m polystyrene (PSL) particles, and 1.5% for 10- μ m oleic acid particles. The efficiency for 3- μ m oleic acid droplets was 35%. Explanations are provided for the difference between liquid and solid particle behavior, and for the low efficiency for the large liquid particles. The collection efficiency for single spore BG was slightly lower than that for 1- μ m PSL.

Keywords Batch bioaerosol collector · Bioaerosol sampler · Retention efficiency · Collection efficiency · *Bacillus atrophaeus* · Spore collection

1 Introduction

Exposure to bioaerosols, especially to pathogenic or allergenic microorganisms, may cause a wide range of respiratory and other health disorders in the general and occupational populations. To monitor air for the presence of bioaerosol particles, batch-type bioaerosol samplers have been developed, but most are designed to be operated with a fixed initial volume of collection liquid and have no provisions for continuously adding makeup liquid to compensate for evaporation, which can limit the sampling period. Several studies have been conducted to evaluate the performance batch type samplers with fixed-initial

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liquid volumes. For example, the sampling performance of the AGI-30 all-glass impinger (ACE Glass Inc., Vineland, NJ), was compared with two filtration sampling methods and was found to be the least efficient sampling method (Lin and Li 1998). A swirling aerosol collector (SKC Inc., Eighty-Four, PA), which is a batch sampler where particles in an air flow of 12.5 l/min are concentrated into 20 ml of liquid (Willeke et al. 1998), was tested for collection efficiency and found to provide better microbial recovery than the AGI-30 impinger (Lin et al. 2000). A swirling batch sampler, developed by Lawrence Berkeley National Laboratory (Masquelier et al. 2003), was shown to achieve air-to-liquid concentration factor rates as high as 275,000/min for particles of 2.5 μm and larger (Mainelis et al. 2006). By varying the operational parameters of the sampler, such as flow rate and the amount of collection liquid, its cutpoint size (aerodynamic particle size for which half of the particles in the inflow stream are collected in the liquid) could be varied from 0.45 to 2.1 μm aerodynamic diameter (AD), thus allowing its collection efficiency curve to be shifted over a range of particle sizes (Mainelis et al. 2006).

A batch-type wetted wall cyclone (BWWC), which samples at a flow rate of 60 l/min and concentrates the particulate matter into 10 ml of liquid, was developed by Sigaev et al. (2006). Aerosol is accelerated as it enters the cyclone body, and larger particles are impacted on the inner wall, which is continuously wetted by liquid. Due to air shear on the cyclone wall region, the liquid develops a swirling motion. The cutpoint size is between 0.5 and 1.0 μm AD.

The BWWC evaluated in this study is a commercially-available system described by Cage et al. (1999). Its operating principle is similar to the system developed by Sigaev et al. (2006). The commercially available BWWC is designed to sample air at a flow rate of 400 l/min and concentrate the particles into a liquid volume of 12 ml. It includes provisions for continuously adding makeup liquid to compensate for evaporation so it can theoretically be operated for extended periods of time. The system was initially developed for the near-real time continuous monitoring and environmental sampling of chemical-based aerosols (Going et al. 1994; Kesavan et al. 2001; Kesavan and Schepers 2006), but it has been evaluated and utilized in a comparative study involving

sampling allergens in outdoor air (Cage et al. 1996; Barnes et al. 2000).

Aerosol enters the cyclone body (Fig. 1), which is constructed of glass or plastic, tangentially through an inlet slot. The cyclone is 62 mm in diameter by 160 mm high and the velocity at the inlet slot is 58 m/s. A batch of 12 ml of collection liquid is injected at the start of the sampling cycle and spins inside the cyclone until the end of the cycle. The height of the paraboloid-shaped spinning body of liquid is continuously monitored with an optical sensor and additional water is injected, as needed, to compensate for evaporation. At the end of the sampling period, the collection liquid is transferred from the BWWC. In this study, unless otherwise indicated, deionized water was used as the collection fluid.

The design and characteristics of many bioaerosol sampling devices have been summarized in review documents (Henningson and Ahlberg 1994; Macher and Burge 2001; Nevalainen et al. 1993); however, because batch-type wetted wall cyclones with provisions for continuously controlling the amount of collection fluid are a relatively recent development, there is not a great amount of information available on these devices. It was the purpose of this study to investigate the sampling performance of the commercially available BWWC from the standpoint of

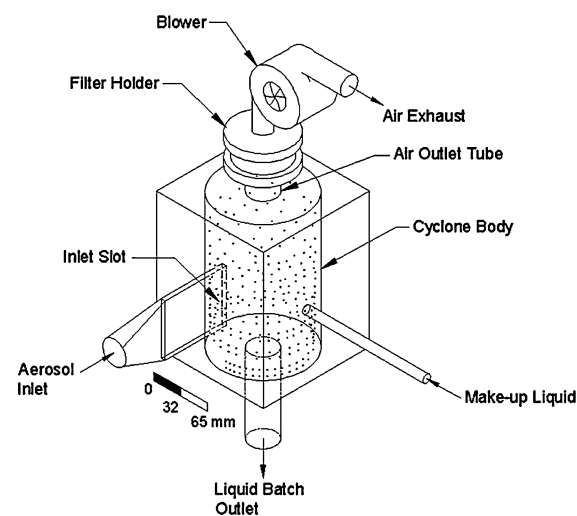


Fig. 1 Test setup of batch-type wetted wall cyclone (BWWC) with an exhaust filter. Some aerosol collection efficiency tests were conducted with the exhaust filter removed, and the blower attached directly to the top of the cyclone

collection efficiency and the ability to retain the collected particles in the collection fluid for extended periods of time.

2 Materials and methods

2.1 Retention testing

We define the sample retention efficiency of the BWWC as the ratio of the number of particles in the hydrosol state after a given time of operation to the number of particles introduced directly into the deionized water used as collection liquid at a time of zero. Generally this parameter is not only a function of time, but also of particle size and type. The retention of particles in the collection liquid of the BWWC was evaluated by dispersing 1- μ m fluorescent polystyrene latex beads (PSL) and *Bacillus atrophaeus* (aka *Bacillus globigii*, BG) spores directly into the collection liquid in the glass cyclone body, and then operating the unit for pre-set time intervals. To determine the number of particles that are aerosolized and escape with the exhaust air, a filter was placed between the top of the BWWC cyclone body and the blower as shown in Fig. 1. Glass fiber air sampling filters, 102 mm in diameter (Type A/D, Pall Corporation, East Hills, NY), were used to collect particles in the exhaust airflow from the cyclone.

During the retention testing with the fluorescent latex beads, 100 μ l of the 1- μ m PSL suspension (Catalog Number R0100B, Duke Scientific, Palo Alto, CA) was added to the collection liquid in the glass cyclone. Another 100 μ l of the test suspension was placed in a glass receptacle to serve as a reference sample. Operation of the BWWC was then started and continued for periods of 5 min, 1, 2, 4, and 8 h. The optical liquid volume controller of the BWWC automatically performed compensation for any liquid evaporation. During testing, a venturi flowmeter (HFC-Digital-1400L, HI-Q Environmental Products Corp, San Diego, CA) was attached to the inlet of the cyclone and subsequently to the outlet to verify that 400 l/min of air was being sampled and exhausted.

At the end of the sampling period, the BWWC liquid was collected, weighed, and then evaporated with a heat gun. Similarly, the liquid associated with

the reference sample was evaporated with the heat gun. Ten milliliters of HPLC-grade ethyl acetate was added to the evaporated samples to dissolve the PSL beads and create a solution for fluorescent analysis. Thirty milliliters of ethyl acetate was added to the exhaust filters to dissolve the PSL beads for analysis. All solutions were analyzed with a fluorometer (Model 109535, Barnstead Turner International, Dubuque, IA) fitted with a narrow band (NB) 540-nm optical excitation filter and a narrow band 590-nm filter as the optical emission filter. After each test the BWWC was thoroughly cleaned to remove any residue from the glass cyclone. Four 1-min sampling cycles were run consecutively, the exhaust filter was removed, and the inside of the glass cyclone was swabbed.

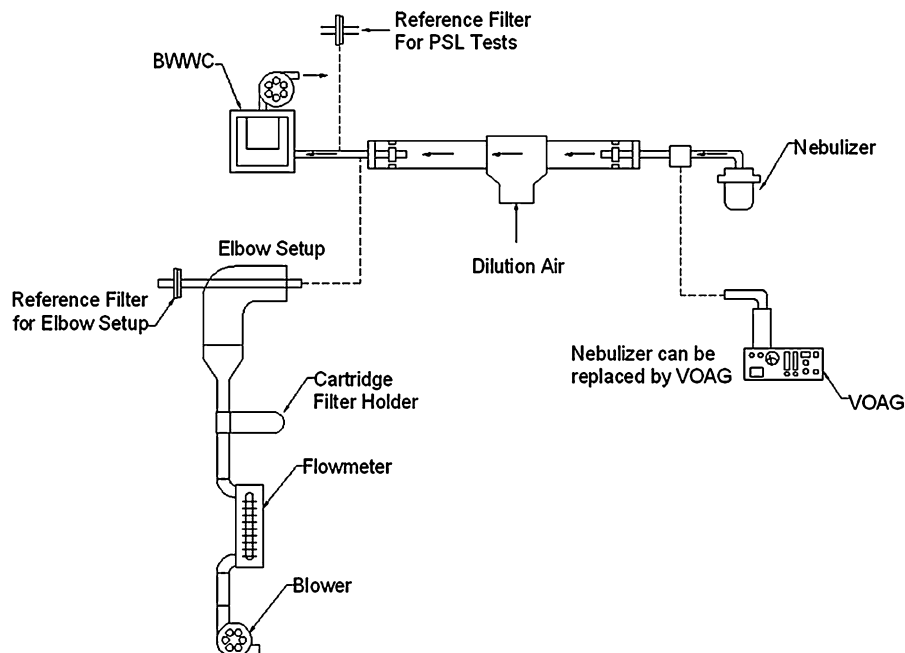
Retention testing was also conducted with BG spores. Fifty milligrams of lyophilized BG powder (US Army Edgewood Chemical Biological Center, Edgewood, MD) were suspended in 5 ml of deionized water by vigorous vortexing and then centrifuged at 4,000 rpm for 9 min to remove traces of the culture medium. The supernatant was aspirated and the pellet was resuspended in 1 l of sterile deionized water to form a stock suspension. One hundred microliters of the stock BG suspension, containing approximately 1×10^8 spores/ml, were dispersed in the 12 ml batch of collection liquid in the BWWC and the sampling cyclone was run for time periods of 5 min, 1, 2, 4, and 8 h. The samples were analyzed by colony counting of the bacteria plated in appropriate dilutions and with a GeneXpert rapid polymerase chain reaction (PCR) machine (Cepheid, Sunnyvale, CA).

To calibrate the PCR machine, a stock suspension (4×10^9 spores/ml) was diluted by factors of ten into a series of suspensions, and the suspensions were analyzed with the PCR machine. Actual concentration of the BG suspension dilutions were determined by colony counting.

2.2 Aerosol testing

The apparatus shown in Fig. 2 was used for testing the aerosol collection efficiency of the BWWC with PSL beads, liquid oleic acid droplets, and BG spores. Here, for a given particle size, the collection efficiency is defined as the ratio of the number of particles in the hydrosol state to the number that enter the sampler in the aerosol state over a fixed period of time.

Fig. 2 Apparatus used for testing the batch-type wetted wall cyclone (BWWC) with aerosols. A vibrating orifice aerosol generator (VOAG) was used for generation of liquid particles and Collison nebulizers were used for generation of polystyrene and *Bacillus atrophaeus* particles. During testing with the polystyrene and *Bacillus atrophaeus* particles, the elbow setup and BWWC alternately sampled the aerosol. For tests with polystyrene particles, a reference filter and the BWWC alternately sampled the aerosol



PSL aerosols were generated with a 24-jet nebulizer (CB-24, BGI Incorporated, Waltham, MA), and BG spore aerosols were generated with a six-jet Collison nebulizer (Model CN-25, BGI Incorporated, Waltham, MA). In the test setup, the aerosol was drawn through a 100-mm diameter test section, mixed with drying/dilution air, and then collected alternately with the BWWC and a reference filter, which was also operated at a flow rate of 400 l/min (Fig. 2).

Testing of the BWWC with PSL was carried out with two particle sizes (1- and 3- μ m diameters). A master suspension of PSL was prepared by diluting a 60-ml bottle of PSL, as received from the vendor, in one liter of deionized water. For each aerosol test, 50 ml of master suspension were loaded into the 24-jet Collison nebulizer and a fresh filter was placed in the exhaust filter holder of the BWWC. The BWWC and the nebulizer were actuated and run simultaneously for 5 min. The BWWC was then replaced with a reference filter and the process was repeated. The hydrosol samples collected by the BWWC were weighed, evaporated with a heat gun, and dissolved in 10 ml of ethyl acetate. The exhaust and reference filters were soaked in 30 ml of ethyl acetate to elute the fluorescent tracer. The fluorescent tracer from the dissolved PSL beads was analyzed

fluorometrically. The aerosol testing using 1- and 3- μ m PSL was repeated with the exhaust filter removed, and the blower attached directly to the top of the cyclone to determine if the filter had an effect on the aerosol sampling efficiency.

Tests were conducted with two sizes of fluorescently tagged oleic acid liquid droplets (3- and 10- μ m diameters) using a protocol that also involved alternately collecting samples with the BWWC and reference filters; however, for these tests the reference samples were acquired using the elbow setup (Fig. 2), which was operated at a flow rate of 100 l/min. Monodisperse aerosols of liquid oleic acid droplets, tagged with a fluorescent tracer (sodium fluorescein), were generated with a vibrating orifice aerosol generator (VOAG, Model 3450; TSI Inc., Shoreview, MN). During testing, the VOAG was adjusted to produce the desired size of particles and an aerodynamic particle sizer (APS) (Model 3321; TSI Inc., Shoreview, MN) was used for assurance that the aerosol size distribution was monodisperse and the aerosol concentration was constant. The particles were sized by impacting a sample on a glass slide coated with an oil-phobic film (Nyebar Type Q, 2.0%; Nye Lubricants, Fairhaven, MA). The diameters of these particles were then measured using an optical microscope (Nikon Eclipse E600; Nikon

Instruments Inc., Melville, NY). The aerodynamic diameter (AD) of the droplets was calculated from the microscopically-measured size, adjusted for flattening of the droplets on a microscope slide according to the method described by Olan-Figueroa et al. (1982), but with a flattening factor of 1.29, and from use of the particle density. Hydrosol samples from the BWWC were weighed and 2.5 ml of hydrosol sample was added to 2.5 ml of isopropyl alcohol. The filters were soaked overnight in 30 ml of a solution of 1:1 (V/V) isopropyl alcohol/deionized water and nine drops of 1N NaOH. The fluorescent solutions were analyzed in the fluorometer with a narrow band 490-nm band pass excitation filter and a sharp cut (SC) 515-nm band pass emission filter. The pH of the samples was adjusted to at least 11 by the addition of 1N NaOH in order to maximize the fluorescence of the solution (Kesavan et al. 2001).

Single spore BG aerosol testing was also conducted with the apparatus shown in Fig. 2, with the aerosol generated by the six-jet Collison nebulizer. For each test involving aerosolization and sample collection, a fresh batch (40 ml) of the same type of BG suspension used in the retention testing was placed in the nebulizer, which was operated at an air pressure of 137 kPa (20 psi gage pressure). The particle size output from the Collison was monitored with the APS, for assurance that the aerosol was monodisperse and of constant concentration.

Samples were alternately collected with the BWWC and the elbow setup (Fig. 2), where the latter was fitted with a 47-mm diameter gelatin filter (catalog number 12602-47-ALK; Sartorius AG, Goettingen, Germany). During operation of the elbow setup, 15 l/min of air was drawn through the gelatin reference filter. At the completion of a test, the gelatin filter was dissolved in 20 ml of a 0.1% Tween-20 aqueous solution. For analysis, 100- μ l samples of the filter suspension and the BWWC hydrosol were spread in appropriate dilutions on Difco tryptic soy agar plates (Becton, Dickinson, and Company, Franklin Lakes, NJ) and incubated for 16 h at 30°C. Five replicate analyses were conducted for each test condition.

As will be noted in the Results and discussion section, there can be losses due to adhesion of solid particles on the internal walls of the cyclone, which degrade the performance of the BWWC. In an attempt to reduce these wall losses, we added

surfactants, either 0.1% Tween-20 or sodium dodecyl sulfate (SDS) (Sigma-Aldrich, St. Louis, MO) to the collection liquid; however, these agents caused foaming of the collection fluid that in turn caused malfunctioning in the liquid control system. We then added anti-foam agent B emulsion (Sigma-Aldrich, St. Louis, MO) to the special collection fluid in 0.01–0.1% concentration to reduce foaming.

All results presented for the retention and aerosol collection efficiency tests are based on at least three replicates, and the data are reported as statistical averages. In the next section, some data are presented graphically with error bars, which represent ± 1 standard deviation about a mean.

3 Results and discussion

3.1 Retention tests

The results of retention tests with 1- μ m polystyrene beads (PSL) are shown in Fig. 3. When the unit is run for 5 min, about 80–85% of the particles remain in the collection liquid. After 1 h, the retention is about 70% of the original material, and as the length of the sampling cycle increases, the retention continues to decrease. After 8 h, only 10% of the original PSL beads are recovered with the collection liquid.

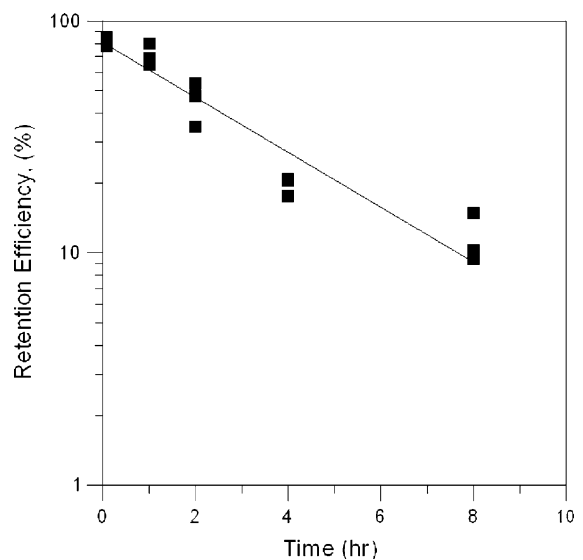


Fig. 3 Retention efficiency of 1- μ m polystyrene beads (PSL) in the batch-type wetted wall cyclone (BWWC) liquid. A known amount of PSL was added to the BWWC at time zero

From visual inspection, the losses occur on the walls of the cyclone in the region above the main body of circulating water, with some losses on the walls of tubing and a holding chamber of a fluid transfer system that is used to remove the hydrosol at the end of a test. Negligible amounts of PSL were collected on the exhaust filter mounted above the cyclone. Lin et al. (1997) conducted tests with all-glass impingers and observed on the order of 10% loss of collected particulate matter after 1 h of operation, which was ascribed to re-aerosolization that occurs as a consequence of the bubbling action in an impinger. Significant bubbling does not occur in the type of BWWC tested in this study, and because the after-filter does not show evidence of PSL particulate matter, it is suggested that periodic wetting and drying of the upper inner area of the cyclone wall is the cause of the retention efficiency degradation. We hypothesize that as the collection water spins in the cyclone, small rivulets break off from the main mass of water and climb the cyclone wall. Some of these rivulets evaporate and leave the particles they contained stranded above the circulating mass of water. To visualize the areas of particle loss, the BWWC was run with the collection water dyed with red food coloring. At the completion of the testing, dried deposits of food coloring were observed above the nominal area washed by the circulating water.

Tests were conducted to determine the amount of material that was recovered from successive 1-min wash cycles. The BWWC first sampled 1- μm PSL aerosol particles for 5 min and the hydrosol associated with that cycle was dumped from the cyclone (first wash). The BWWC was then operated on 1-min cycles, but with no additional aerosol being sampled. In Fig. 4, the amount removed in a particular cycle is compared to the total amount extracted tracer. The results indicate that the single wash procedure used to recover particles from the BWWC is quite effective. The first wash recovered 88% of the total recovered in the five washes, while the remaining four washes recovered 12%. However, the particles adhering to the cyclone wall above the circulating liquid were not effectively removed during the wash cycles.

The retention testing was repeated with BG spores using the GeneXpert for analysis. Results from the GeneXpert were calculated from the calibration curve shown in Fig. 5, which relates the number of PCR

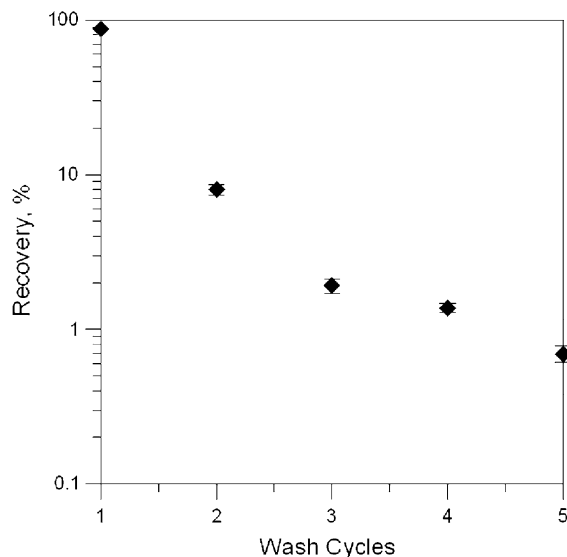


Fig. 4 Fraction of 1- μm polystyrene bead (PSL) particles recovered during successive 1-min washes. The total for the five washes is assumed to be 100%. Error bars are ± 1 standard deviation about a mean value

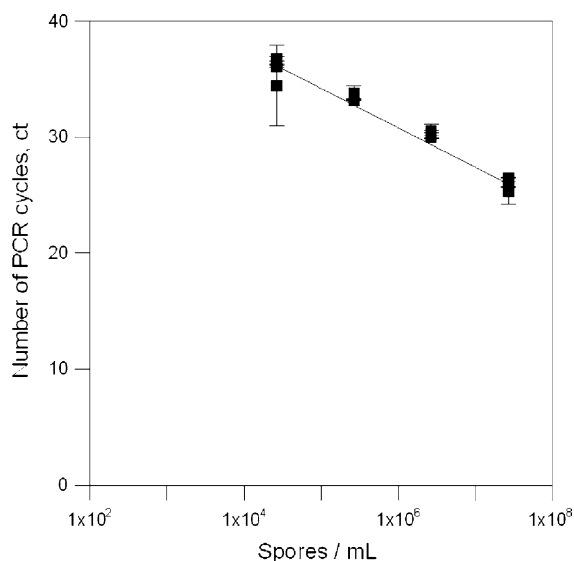


Fig. 5 Calibration of GeneXpert PCR with *Bacillus atrophaeus* (aka BG) spores. Standard error bars are shown for each mean value

cycles (*ct*) to the concentration of spores in the suspension (spores/ml). The results of the retention tests for BG spores are shown in Fig. 6 together with the previously obtained PSL results. Due to the exponential relationship between *ct* and BG spore concentration, the errors in the *ct* values are magnified

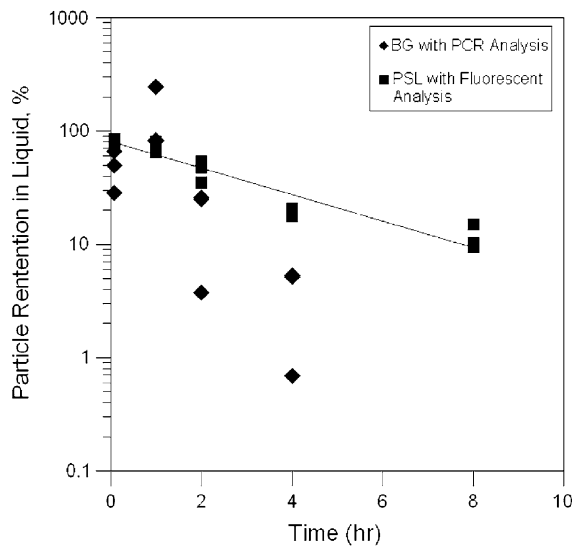


Fig. 6 Retention of *Bacillus atrophaeus* (BG) and polystyrene beads (PSL) in the batch-type wetted wall cyclone (BWWC) collection liquid. The BG spores were assayed using PCR, and the PSL was analyzed fluorometrically. The line is drawn through the data points associated with the PSL particle testing

when they are converted to concentration. The data scatter shown in Fig. 6 suggests that the GeneXpert does not allow accurate determination of BG in the hydrosol state of a BWWC. Similar observations regarding the use of the Genexpert for quantitative purposes, emphasizing careful optimization of the conditions and primer selection, have been offered by other researchers (Ulrich et al. 2006; Ferre 1992; Selvapandian et al. 2005).

3.2 Aerosol tests

The results of aerosol tests conducted with PSL and oleic acid particles are shown in Fig. 7. The PSL test results indicate an efficiency of 50–60% for 1- and 3- μ m diameter particles. The results agree reasonably well with those from the vendor that manufactures the apparatus of Cage et al. (1999) who reports efficiencies of about 55–80% for PSL aerosols of these sizes. We measured an efficiency of 35% for 3- μ m oleic acid liquid particles and 1.5% for the 10- μ m liquid particles. The higher efficiency for PSL vis-à-vis oleic acid may be due to re-entrainment of solid PSL particles that strike the wall of the aerosol inlet slot, as compared with the action of droplets that adhere to the surfaces of the slot when they impact it.

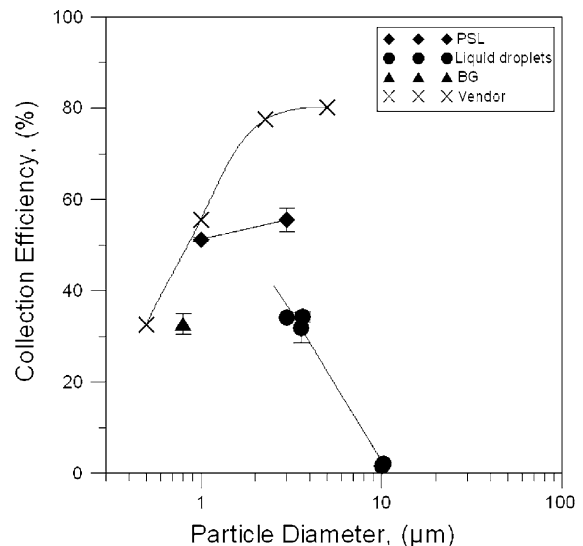


Fig. 7 Aerosol collection efficiency of single spores of *Bacillus atrophaeus* (BG) based on culturability, liquid particles and polystyrene (PSL) beads in the batch-type wetted wall cyclone (BWWC) based on 5-min testing periods. The efficiency values marked “vendor” are added for comparison. Error bars on the data points are ± 1 standard deviation about the mean

Visual inspection of the cyclone after use with liquid droplets showed signs of such deposition; however, the design of the system did not lend itself to accurate quantification of the phenomenon. The aerosol collection efficiency for the 10- μ m liquid oleic acid particles, i.e. 1.5%, is low compared with a typical bioaerosol sampling cyclone where the efficiency can be on the order of 90% (Hu and McFarland 2007).

The after-filter of the BWWC was used to test whether there was re-aerosolization occurring; however, efficiency testing was repeated with the exhaust filter removed and blower attached directly to the top of the cyclone. The results for tests with 1- and 3- μ m PSL showed efficiencies that were 6–8% higher than with the filter in place. The difference may be due to the filter causing a reduction of the rotational rate of the vortex in the cyclone body (Fig. 1) which, in turn, reduces the centrifugal effects on the particles in the tube.

The aerosol collection efficiency for a single-spore BG aerosol is also shown in Fig. 7. The efficiency is approximately 32%, which is lower than that for 1- μ m PSL particles, which is about 50%. This difference is likely attributable to two phenomena. First, the aerodynamic size of the BG is about

0.85 μm , which is less than that of the PSL (1.02 μm AD), so the difference in efficiencies may be due to the inherent fractionation characteristics of the cyclone; namely, that larger particles are more efficiently collected. However, by comparing the slope of a line connecting the BG and PSL data with the slope of the “vendor” curve in the same particle size region of Fig. 7, the difference in aerosol collection efficiency of BG and PSL appears to be greater than that attributable to only cyclone fractionation characteristics. The second reason is that the BG particles may adhere better to the inner surfaces of the cyclone and thus are not as effectively removed from the cyclone with 12-ml liquid batch at the end of the sampling period.

Regarding the addition of surfactant to the collection liquid in the cyclone to enhance particle recovery, the approach caused the formation of foam and the foam interfered with an optical liquid level control system. Too little water (on the order of 50–75% of normal) was introduced into the cyclone by the automated liquid volume control system and the amount of water collected was found to be highly variable. When the anti-foam agent B emulsion (Sigma-Aldrich, St. Louis, MO) was added to the surfactant solution, it reduced the foam formation; however, it caused the collection fluid to become too turbid to accommodate satisfactory operation of the optical liquid control system.

4 Conclusions

The retention efficiency of particles in the collection liquid of the BWWC was tested with 1- μm PSL particles and BG spores, where the latter was evaluated with the aid of a GeneXpert PCR machine. When the BWWC is run for 5 min, 80–85% of the initial particles are retained in the hydrosol state, while the remainder is lost to the walls of the cyclone or the tubing and holding chamber. After 1 h, 70% of the original material remains, and as the length of the sampling cycle increases more material continues to be lost. After 8 h approximately 10% of the original particulate matter is retained in the batch of liquid transferred from the sampler. The losses were primarily observed on the wall of the cyclone above the main mass of circulating water. Little material was lost due to aerosolization of the collection liquid.

Reliable retention efficiency results could not be obtained with the GeneXpert due to inherent variability of the method.

The collection efficiency of the BWWC was 51% for 1- μm PSL, 55% for 3- μm PSL, 33% for 3- μm oleic acid, and 1.5% for 10- μm oleic acid droplets. It is possible that the higher efficiency with 3- μm PSL as opposed to 3- μm oleic acid is due to the solid particles bouncing off of internal surfaces and being re-entrained, particularly on the walls of the entrance slot of the cyclone, whereas liquid particles adhere to these surfaces after impact. This loss on the inlet slot is particularly significant for 10- μm liquid oleic acid droplets, where only 1.5% of the aerosol particles are recovered from the collection liquid. The efficiency with single spore BG aerosol particles was found to be lower (32%) than that for 1- μm PSL particles (51%). This is due to the smaller size of the BG particles and perhaps to a higher adherence of BG to the cyclone inner wall.

Overall, the retention of collected samples in a batch type WWC is reduced with time and the collection efficiency is dependent upon the type of particle (liquid or solid) as well as the particle size. Design modification to the inlet slot would improve the collection efficiency for large particles.

References

- Barnes, C., Schreiber, K., Pacheco, F., Landuyt, J., Hu, F., & Portnoy, J. (2000). Comparison of outdoor allergenic particles and allergen levels. *Annals of Allergy, Asthma & Immunology*, 84, 47–54.
- Cage, B. R., Gorman, P. G., Going, J. E., Thornburg, M. J., & Soderberg, D. R. (1999). Continuous emission monitoring system. US patent 5,861,316. January 19, 1999.
- Cage, B. R., Schreiber, K., Barnes, C., & Portnoy, J. (1996). Evaluation of four bioaerosol samplers in the outdoor environment. *Annals of Allergy, Asthma & Immunology*, 77, 401–406.
- Ferre, F. (1992). Quantitative or semi-quantitative PCR: Reality versus myth. *PCR Methods and Applications*, 2, 1–9.
- Going, J., Cage, B., Thornburg, M., & Soderberg, D. R. (1994). Prototype near real-time monitor for Lewisite in stack gas. Proceedings of the 1994 international incineration conference: Thermal treatment of radioactive, hazardous chemical, mixed munitions, and pharmaceutical wastes. Houston, Texas, May 9–13, 1994. Available from Office of Environment, Health and Safety, University of California at Irvine.

- Henningson, E. W., & Ahlberg, M. S. (1994). Evaluation of microbiological aerosol samplers: A review. *Journal of Aerosol Science*, 25(8), 1459–1492. doi:[10.1016/0021-8502\(94\)90219-4](https://doi.org/10.1016/0021-8502(94)90219-4).
- Hu, S., & McFarland, A. R. (2007). Numerical performance simulation of a wetted wall bioaerosol sampling cyclone. *Aerosol Science and Technology*, 44, 160–168. doi:[10.1080/02786820601124065](https://doi.org/10.1080/02786820601124065).
- Kesavan, J., Doherty, R. W., Wise, D. G., & McFarland, A. R. (2001). *Factors that affect fluorescein analysis*. U.S. Army Edgewood Chemical Biological Center, Aberdeen Proving Ground, Edgewood, MD. Report ECBC-TR-208. AD-A, 397, 677.
- Kesavan, J., & Schepers, D. (2006). *Characteristics and sampling efficiencies of BWWC and preproduction omni model aerosol samplers*. U.S. Army Edgewood Chemical Biological Center, Aberdeen Proving Ground, Edgewood, MD. Report (ECBC-TN-027), October 2006.
- Lin, X., & Li, C.-S. (1998). The effect of sampling time and flow rates on the bioefficiency of three fungal spore sampling methods. *Aerosol Science and Technology*, 28, 511–522. doi:[10.1080/02786829808965542](https://doi.org/10.1080/02786829808965542).
- Lin, X., Reponen, T., Willeke, K., Wang, Z., Grinshpun, S., & Trunov, M. (2000). Survival of airborne microorganisms during swirling aerosol collection. *Aerosol Science and Technology*, 32, 184–196. doi:[10.1080/027868200303722](https://doi.org/10.1080/027868200303722).
- Lin, X., Willeke, K., Ulevich, V., & Grinshpun, S. (1997). Effect of sampling time on the collection efficiency of all-glass impingers. *American Industrial Hygiene Association Journal*, 58, 480–488. doi:[10.1080/15428119791012577](https://doi.org/10.1080/15428119791012577).
- Macher, J. M., & Burge, H. A. (2001). Sampling biological aerosols. In: Cohen, B.S. (ed). *Air sampling instruments for evaluation of atmospheric contaminants* (Chapter 23, 9th ed.). American Conference of Government Industrial Hygienists, Cincinnati, OH.
- Mainelis, G., Masquelier, D. A., Willeke, K., Makarewicz, A., Dzenitis, J., & Milanovich, F. P. (2006). Performance of a compact air-to-liquid aerosol collector with high concentration rate. *Journal of Aerosol Science*, 37, 645–657. doi:[10.1016/j.jaerosci.2005.06.004](https://doi.org/10.1016/j.jaerosci.2005.06.004).
- Masquelier, D. A., Milanovich, F. P., & Willeke, K. (2003). High air volume to low liquid volume aerosol collector. U.S. Patent 6,520,034 B1.
- Nevalainen, A., Willeke, K., Liebhaber, F., Pastuszka, J., Burge, H., & Henningson, E. (1993). *Bioaerosol sampling: aerosol measurement principles, techniques, and applications* (pp. 471–492). New York: Van Nostrand Reinhold.
- Olan-Figueroa, E., McFarland, A. R., & Ortiz, C. A. (1982). Flattening coefficients for DOP and oleic acid droplets deposited on treated glass slides. *American Industrial Hygiene Association Journal*, 43, 395–399. doi:[10.1202/0002-8894\(1982\)043<0395:FCFDAO>2.3.CO;2](https://doi.org/10.1202/0002-8894(1982)043<0395:FCFDAO>2.3.CO;2).
- Selvapandian, A., Stabler, K., Ansari, N. A., Kerby, S., Riemenschneider, J., Salotra, P., et al. (2005). A novel semiquantitative fluorescence-based multiplex polymerase chain reaction assay for rapid simultaneous detection of bacterial and parasitic pathogens from blood. *Journal of Molecular Diagnostics*, 7(2), 268–275.
- Sigaev, G. I., Tolchinsky, A. D., Sigaev, V. I., Soloviev, K. G., Varfolomeev, A. N., & Chen, B. T. (2006). Development of a cyclone-based aerosol sampler with recirculating liquid film: theory and experiment. *Aerosol Science and Technology*, 40, 293–308. doi:[10.1080/02786820600596891](https://doi.org/10.1080/02786820600596891).
- Ulrich, M. P., Christensen, D. R., Coyne, S. R., Craw, P. D., Henchal, E. A., Sakai, S. H., et al. (2006). Evaluation of the Cepheid GeneXpert system for detecting *Bacillus anthracis*. *Journal of Applied Microbiology*, 100, 1011–1016. doi:[10.1111/j.1365-2672.2006.02810.x](https://doi.org/10.1111/j.1365-2672.2006.02810.x).
- Willeke, K., Lin, X., & Grinshpun, S. (1998). Improved aerosol collection by combined impaction and centrifugal motion. *Aerosol Science and Technology*, 28, 439–456. doi:[10.1080/02786829808965536](https://doi.org/10.1080/02786829808965536).