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Evaluation of Pump Pulsation in Respirable Size-Selective Sampling: Part II. Changes in Sampling Efficiency

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Abstract

This second, and concluding, part of this study evaluated changes in sampling efficiency of respirable size-selective samplers due to air pulsations generated by the selected personal sampling pumps characterized in Part I (Lee E, Lee L, Möhlmann C ***et al.*** Evaluation of pump pulsation in respirable size-selective sampling: Part I. Pulsation measurements. Ann Occup Hyg 2013). Nine particle sizes of monodisperse ammonium fluorescein (from 1 to 9 μm mass median aerodynamic diameter) were generated individually by a vibrating orifice aerosol generator from dilute solutions of fluorescein in aqueous ammonia and then injected into an environmental chamber. To collect these particles, 10-mm nylon cyclones, also known as Dorr-Oliver (DO) cyclones, were used with five medium volumetric flow rate pumps. Those were the Apex IS, HFS513, GilAir5, Elite5, and Basic5 pumps, which were found in Part I to generate pulsations of 5% (the lowest), 25%, 30%, 56%, and 70% (the highest), respectively. GK2.69 cyclones were used with the Legacy [pump pulsation (PP) = 15%] and Elite12 (PP = 41%) pumps for collection at high flows. The DO cyclone was also used to evaluate changes in sampling efficiency due to pulse shape. The HFS513 pump, which generates a more complex pulse shape, was compared to a single sine wave fluctuation generated by a piston. The luminescent intensity of the fluorescein extracted from each sample was measured with a luminescence spectrometer. Sampling efficiencies were obtained by dividing the intensity of the fluorescein extracted from the filter placed in a cyclone with the intensity obtained from the filter used with a sharp-edged reference sampler. Then, sampling efficiency curves were generated using a sigmoid function with three parameters and each sampling efficiency curve was compared to that of the reference cyclone by constructing bias maps. In general, no change in sampling efficiency (bias under ±10%) was observed until pulsations exceeded 25% for the DO cyclone. However, for three models of pumps producing 30%, 56%, and 70% pulsations, substantial changes were confirmed. The GK2.69 cyclone showed a similar pattern to that of the DO cyclone, i.e. no change in sampling efficiency for the Legacy producing 15% pulsation and a substantial change for the Elite12 producing 41% pulsation. Pulse shape did not cause any change in sampling efficiency when compared to the single sine wave. The findings suggest that 25% pulsation at the inlet of the cyclone as measured

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by this test can be acceptable for the respirable particle collection. If this test is used in place of that currently in European standards (EN 1232–1997 and EN 12919-1999) or is used in any International Organization for Standardization standard, then a 25% pulsation criterion could be adopted. This work suggests that a 10% criterion as currently specified in the European standards for testing may be overly restrictive and not able to be met by many pumps on the market. Further work is recommended to determine which criterion would be applicable to this test if it is to be retained in its current form.

Keywords

amplitude; frequency; penetration shift; pulsation magnitude; pump pulsation; respirable cyclones; sampling efficiency

INTRODUCTION

The findings presented in Part I of this study (Lee *et al.*, 2013) verified that many personal sampling pumps used in the field today produce large pulsations that modulate air flow in the sampling train. Evidently, the pulsation dampeners prescribed in the 1970s (Anderson *et al.*, 1971; Lamonica and Treaftis, 1972; Caplan *et al.*, 1973; Blachman and Lippmann, 1974; McCawley and Roder, 1975), and incorporated into the pumps tested, have not provided the anticipated constancy of flow. Modulations in the velocity of particles going into and through a cyclone pre-collector may alter the penetration characteristics of the cyclone and the total mass collected, thus biasing the computation of particulate concentrations to which workers are exposed. The goal of this study was to evaluate this concern.

METHODS

Experimental setup

Figure 1 shows the schematic of the experimental setup. Nine sizes of monodisperse particles, nominally 1, 2, 3, 4, 5, 6, 7, 8, and 9 μm mass median aerodynamic diameter (MMAD), were generated individually by a vibrating orifice aerosol generator (model 3450; TSI Inc., St Paul, MN, USA). The respirable convention includes particles up to 15 μm MMAD and mass is proportional to the cube of the diameter. Variations in the efficiency of particles collected in the range 10–15 μm MMAD, therefore, could contribute substantially to the total mass collected. However, this size range was excluded in this study because it is also the case that variations in particle generation and dispersion increase with size, which would lead to considerable uncertainty in the results. Dilute solutions of fluorescein in aqueous ammonia electrostatically neutralized using a Kr-85 aerosol neutralizer (model 3054A; TSI Inc.) were injected into an aluminum calm air chamber that was built for a previous study (Feather and Chen, 2003). An aerodynamic particle sizer (model 3321; TSI Inc.) was used to measure the size distribution of the particles before and after sampling to verify that the MMADs were close to the intended size and that the geometric standard deviations (GSD) were <1.2. Polyvinyl chloride filters with a 5-μm pore size were used in all the samplers. Each sampler was connected to a 91.4 cm (36 in.) length of Tygon®R3603 tubing. When using 10-mm nylon Dorr-Oliver (DO) cyclones (Sensidyne, LP, Clearwater, FL, USA), tests were conducted at the manufacturer's recommended flow rate of 1.7l min^{-1} flow. Lee *et al.* (2010), however, found that sampling with GK2.69 cyclones (BGI Inc., Waltham, MA, USA) best fit the American Conference of Governmental Industrial Hygienists (ACGIH)/ International Organization for Standardization (ISO)/ Comité Européen de Normalisation (CEN) respirable convention when using a flow of 4.4l min^{-1}, instead of the 4.2l min^{-1} flow recommended by the manufacturer and Kenny and Gussman (1997). Therefore, 4.4l min^{-1} was used when testing with the GK2.69 cyclones.

One respirable cyclone (either DO or GK2.69 cyclone) and one sharp-edged sampler were used as references. The sharp-edged sampler, 48.6 mm long with 26.0 mm inner diameter, operated at the same flow rate of respirable cyclone. The reference samplers were connected to the laboratory vacuum to provide pulse-free flows that were regulated by mass air flow controllers (model GFC 17; Aalborg, Orangeburg, NY, USA). The sampling pumps used are described in our previous paper (Lee *et al.*, 2013) and included the Basic5, Elite5, GilAir5, HFS513, and Apex IS medium volumetric flow rate pumps and the Elite12 and Legacy high-volumetric flow rate pumps.

The uniformity within the calm air chamber was evaluated by dispersion of monodisperse particles with MMAD's of approximately 2, 4, and 6 μm. Two cyclone types, the DO and GK2.69 cyclones, were tested. These tests revealed that the chamber could house no more than three cyclones and one sharp-edged reference sampler without disrupting uniformity of particle dispersion [overall coefficient of variation (CV) < 10%]. For example, the CV of sampling efficiencies with 4 μm MMAD was 12.9% when four DO cyclones and one sharp-edged reference sampler were in place. This dropped to 4.1% when three DO cyclones and the reference sampler were in place.

For this reason, only four samplers including either three DO or three GK2.69 cyclones and one sharp-edged reference sampler were placed in the chamber simultaneously for each experimental run. Since one of the three cyclones and the sharp-edged sampler were always used as references, only two cyclone/ pump pairs could be included in each run. Paired with DO cyclones were as follows:

- the Apex IS and the Basic5 pumps,
- the Elite5 and the GilAir5 pumps, and
- the HFS513 pump and a piston setup that simulated a pump that generates a single sine wave pulsation based on the fundamental frequency and amplitude of the HFS513 pump.

The GK2.69 cyclones were paired with the Elite12 and the Legacy pumps. These medium and high flow rate pumps were selected based on the findings presented in Part I of this study (Lee *et al.*, 2013).

Three pumps per model and three cyclones per type were randomly assigned for each experimental run to randomize variations between pumps for the same model and between cyclones for the same type. After each experimental run, each filter was placed in 10 ml of 5% ammonium hydroxide to extract the fluorescein. Luminescent intensities were measured with a luminescence spectrometer (model LS50B; Perkins-Elmer, Waltham, MA, USA). All three cyclones and the sharp-edged reference sampler were washed after each run to prevent contamination of subsequent collection (Chen and Huang, 1999). Three replicates were performed for each particle size.

In addition, the findings presented in Part I of this study (Lee *et al.*, 2013) suggested that the shapes of pulses might be as important as the amplitudes and frequencies. Six out of 11 sampling pump types did not generate, nor approximate, single sine wave fluctuations. The HFS513 pump (PP = 25%) generated the most deviant shape (Fig. 2) compared to the other pump types and was therefore selected for experiments with the DO cyclone sampler. As shown in Fig. 3, a piston system, comprising of a ET-139 shaker and a PA-141 amplifier (Labworks Inc., Costa Mesa, CA, USA), a DS345 function generator (Stanford Research Systems, Sunnyvale, CA, USA), and a bellows (p/n 150-96-4-1; Standard Bellows Company, Windsor Locks, CT, USA), was set up to generate single sine wave fluctuations. This sine wave corresponded to the fundamental frequency and amplitude of the fluctuations generated by the HFS513 pump.

Data analysis

Sampling efficiencies were obtained by dividing the luminescent intensity of the fluorescein extracted from the filter placed in each cyclone by the intensity obtained from the filter used with the sharp-edged reference sampler. The means and standard deviations from three replicates for each test condition were calculated and sampling efficiency curves were generated using a sigmoid function with three parameters ($y=\frac{a}{1+e^{-\left(\frac{x-x_0}{b}\right)}}$, where x = sampling efficiency and a, b, x_0 = constant coefficients). The standard procedure for comparing cyclone performance to a reference is through the construction of bias maps as recommended by the EN 13205 (Workplace atmospheres: assessment of performance of instruments for measurement of airborne particle concentrations; CEN, 2002). Bias maps are a convenient and visual presentation of the deviation for any combination of median diameter and GSD that describes a unimodal, log-normally distributed aerosol, as is typical for workplace environments. Each sampling efficiency curve was compared to the efficiency curve of the reference cyclone (except for the piston system). The sampling efficiency curve of the piston system was compared to that of the HFS513 pump to determine the shape effect. Each of these bias maps demonstrates conformity in performance of one sampler to another sampler (the corresponding reference cyclone). The shaded areas within the bias maps (Figs 4–7) are those areas which the EN 13205 standard disregards in assessment because the associated MMAD/GSD combinations are rarely presented in the field. A small shift in the sampling efficiency curve sometimes produced significant changes in bias. Generally, bias is considered acceptable if it falls between ±10% (Bartley *et al.*, 1994; Görner *et al.*, 2001).

RESULTS

Table 1 summarizes the characteristics of the pulsations resulting from the combinations of cyclones and pumps evaluated.

Comparative efficiency curves for the DO cyclones (pulsating flow versus non-pulsating flow) are presented in Figs 4–6. Each data point represents the average of three replicates. When the pulsation was <25% (i.e. the Apex IS and HFS513), performance of the cyclone was essentially unchanged. These maps show less than ±5% bias over the area of interest, i.e. the unshaded area. Negative bias indicates an underestimation of particle concentration by cyclone/pump configurations compared to the reference cyclone. The estimated 50% cut-points ($_{50}d_{ae}$) were 3.98 μm for the Apex IS and 3.90 μm for the HFS513, conforming well to the 4.0-μm cut-point in the ACGIH/ISO/ CEN respirable convention.

On the other hand, the bias maps for the DO cyclones when used with the GilAir5, Elite5, and Basic5 pumps show substantial shifts in sampling efficiencies compared to the reference, especially for particles having MMAD between 2–6 μm. The magnitudes of shift increased with increasing pulsation magnitudes, i.e. GilAir5 (PP = 30%) < Elite5 (PP = 56%) < Basic5 (PP = 70%). Bias reported by these maps was >10% relative to the reference. The biases ranged from 0 to −15% with the GilAir5 pump, from −10 to −30% with the Elite5 pump, and from −15 to −45% with the Basic5 pump. The estimated 50% cut-points were 3.58 μm for the GilAir5, 3.35 μm for the Elite5, and 3.05 μm for the Basic5.

Figure 6 also shows the result of sampling efficiency due to pulse shape. The sampling efficiency curves of the DO cyclone connected to the HFS513 pump (PP = 25%) generating nearly sinusoidal flows (i.e. one major frequency with minor additional harmonics), piston setup, and a mass flow controller (i.e. non-pulsation) were similar to the ACGIH/ISO/ CEN respirable convention (Fig. 6). The bias for the HFS513 against the piston system was <6%. These results indicate that the shape of pulsation did not cause a significant effect on sampling efficiency for the test condition.

As shown in Fig. 7, for the GK2.69 cyclone, sampling efficiency curves for the Legacy pump (PP = 15%) and the non-pulsating air flow were very similar, but a substantial shift in sampling efficiency was observed for the Elite12 pump (PP = 41%). As expected from the sampling efficiency curves, the bias for the Legacy was <5% compared to the non-pulsating flow. In contrast, the GK2.69 cyclone/Elite12 pump configuration exhibited bias from 0 to −15%. The 50% cut-points were 3.54 μm for the Elite12 and 3.87 μm for the Legacy pump.

DISCUSSION

Bartley *et al.* (1984) reported considerable penetration shifts of the DO cyclone at two combinations of frequency (f) and pulsation amplitude (PA) for the particle size distribution between 2.0 and 5.5 μm, when compared to the penetration efficiency at pulse-free flow. The combinations tested were [f (Hz), PA (l min^{-1})] of [66, 0.91] and [34, 1.11]. Our study for the DO/GilAir5 combination at [36.6, 0.98] resulted in a similar performance compared to one of Bartley's experiments, i.e. a negative shift at [34, 1.11].

Berry (1991) reported changes in penetration using the SIMPEDS cyclone with sinusoidal flow at 20, 95, 200, and 255 Hz, but he only tested three particle sizes: 3.5-, 4.5-, and 5.5-μm d_{ae}. PAs were calculated based on the fundamental frequency and cosine and sine coefficients of the Fourier analysis, and the amplitudes varied. Note that Berry (1991) defined PA as the ratio of the peak-to-peak amplitude of the pulsation over the mean flow, i.e. twice the normalized PA in Table 1. For the 20-Hz sinusoidal flow having PAs of 0.70, 0.56, and 0.35, almost no difference in penetration when compared to a constant flow was observed up to 4.5-µm $d_{ae.}$ With 5.5-µm d_{ae} particles, however, the 20-Hz flow caused about +20% difference. For the 95-, 200-, and 255-Hz sinusoidal flows, the changes in cyclone penetration were negative for all particle sizes and became increasingly negative with increasing PA. The ranges in PA for these conditions were 0.19–0.52 for 95 Hz, 0.05–0.66 for 200 Hz, and 0.03–0.13 for 255 Hz. Unfortunately, Berry (1991) did not derive an expression for cut-point as a function of fundamental frequency and amplitude that would provide the point of inflection where sampling efficiency shift transitions from positive to negative. In this study, the fundamental frequency ranged from 24.4 to 36.6 Hz. Only one condition of the Elite5 [f (Hz), normalized PA] = [24.4, 0.86] was close to Berry's (1991) [f (Hz), normalized PA] = [20, 0.84]. The findings of these two studies diverge. As shown in Fig. 5, the Elite5 showed a negative shift against non-pulsating flow although the point estimates of efficiency about 6 µm show an overestimation (i.e. positive). The reason for this divergence is not readily apparent; differences in experimental setup may account, at least in part, for the disagreement.

The HFS513 pump, which most deviated from a single sine wave among the medium volumetric flow rate pumps in this study, did not show a significant change in sampling efficiency. Although the piston setup did not generate sine wave harmonics as did the HFS513 pump, there may in practice be little difference because the HFS513 pump generated one major sine wave with minor additional harmonics. Although most sampling pumps tested in this study showed pulsation patterns that were not single sine waves but not considerably different to the corresponding single sine waves, it is possible that there may exist pumps with flows that deviate further, which may show an effect of pulse shape.

The findings should provide useful information to pump manufactures. For example, pump manufactures could design products not to exceed a particular magnitude of pulsation (e.g. 25% at the inlet of the DO cyclone). The results also inform industrial hygienists, compliance officers, and regulators about the pulsation effects on respirable particle collection even with pulsation dampener(s) installed in a pump. This study further indicates that 25% pulsation measured at the inlet of a cyclone can be an acceptable pump pulsation (PP) in respirable particle collection. This criterion is not the same as the recommended 10% pulsation by the EN 1232-1997 (CEN, 1997) and the EN 12919-1999 (CEN, 1999). Since the test conditions of measuring PPs were not the same (i.e. at 20 cm upstream of a flow resistor in both EN standards and at the inlet of a cyclone in this study), the criterion for acceptable pulsation might differ. It seems that the pulsation readings using a flow resistor are lower than those at the inlet of the cyclone for the medium flow rate pumps (Lee *et al.*, 2013). However, since this observation was based on testing few pump models, a more extensive study might be necessary. This study used only one particle material, while different penetration shifts of various cyclones have been observed when tested with different particle materials (Chen and Huang, 1999). Different sampling efficiencies were reported by Kenny and Lidén (1991) when sampling polyvinyl acetate (density 1.2 g cm^{-3}) particles and silicone oil particles. Since these factors were not comprehensively investigated in this study, it may be necessary to perform an additional study using other sampler types and different particle materials. Although we did not observe a relationship between filter loading and pulsations, a further study on this possible interaction is also recommended.

CONCLUSIONS

The results show that the magnitude of air flow pulsations generated by some personal sampling pumps currently in use significantly alter collection efficiency when used for sampling respirable aerosols. Pumps generating pulsations ≥30% of mean flow may, therefore, underestimate exposure. Standard organizations should reconsider recommendations in light of these findings. Currently, the ISO technical committee (TC) 146 (air quality)/subcommittee (SC) 2 (workplace atmosphere)/working group (WG) 9 (pump performance) is working on a new standard regarding requirements and test methods for personal sampling pumps. Both EN standards and the ISO project have adopted a test procedure and a 10% pulsation criterion without corroborating technical support. Due to the time limitations on developing an ISO standard, the findings of this study will not be included in the current ISO activity but are planned to be delivered to the ISO TC 146/SC 2/WG 9 when the standard is next revised.

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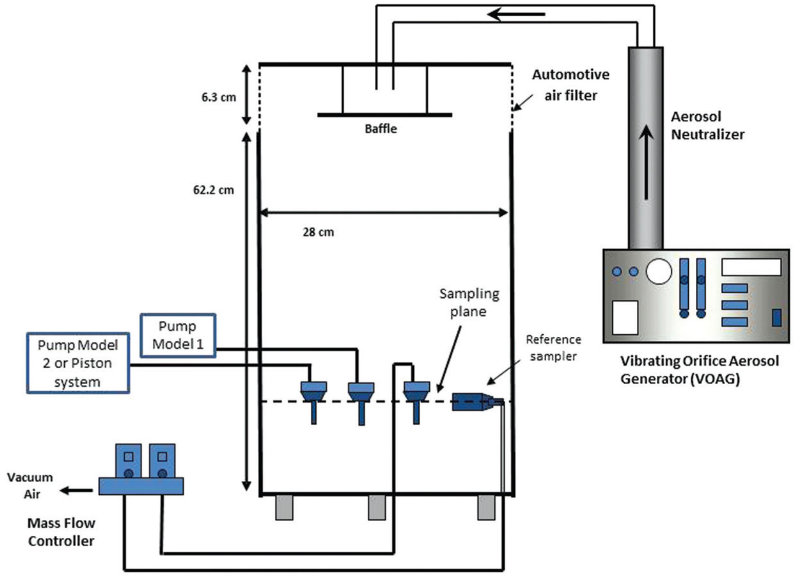

Fig. 1.
Experimental setup using monodisperse particles.

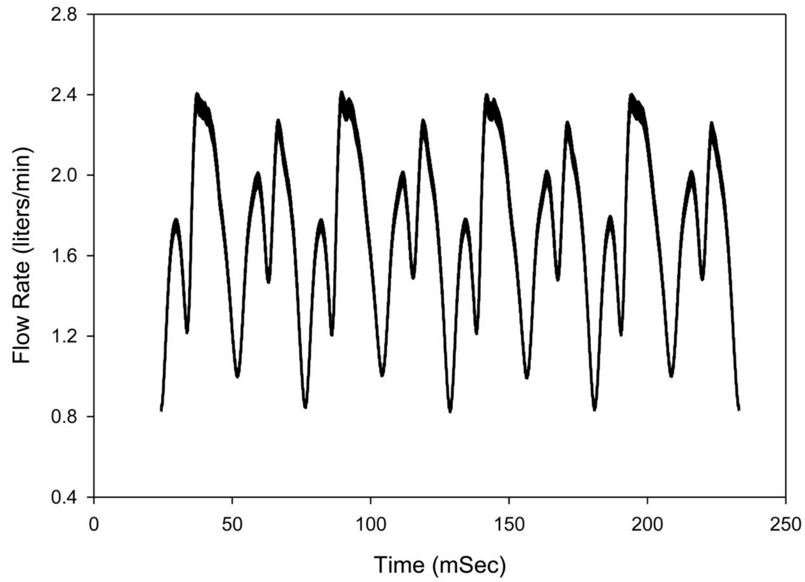

Fig. 2.
Pulsation shape of the HFS513 pump.

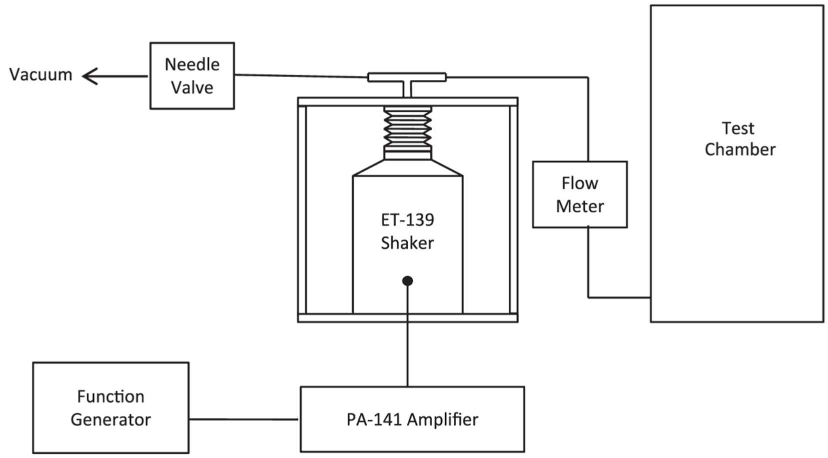

Fig. 3.
Piston setup to generate pure sine waves.

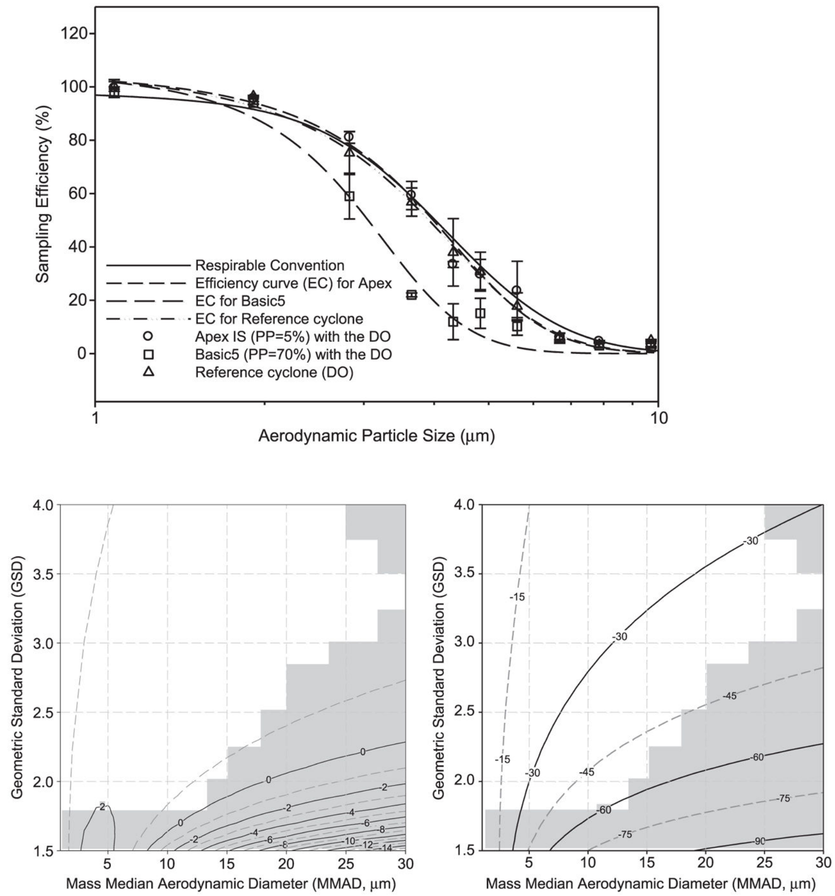

Fig. 4.

Sampling efficiency (SE) curves and bias maps for the DO cyclone when using the Apex IS (left, PP = 5%) and the Basic5 pumps (right, PP = 70%) referenced to a pulse-free vacuum (D_{50} of the reference DO cyclone = 3.91 μm with 50.0% SE).

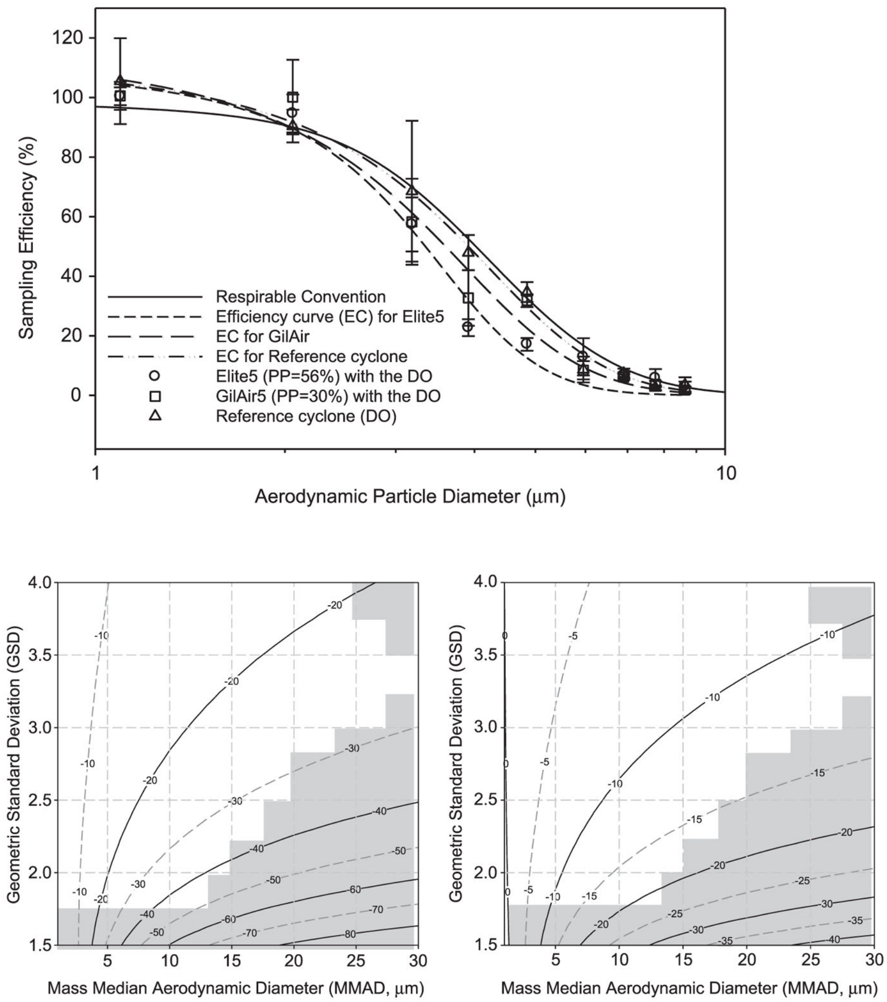

Fig. 5.

Sampling efficiency (SE) curves and bias maps for the DO cyclone when using the Elite5 (left, PP = 56%) and the GilAir5 (right, PP = 30%) referenced to a pulse-free vacuum (D_{50} of the reference DO cyclone = 3.91 μm with 49.9% SE).

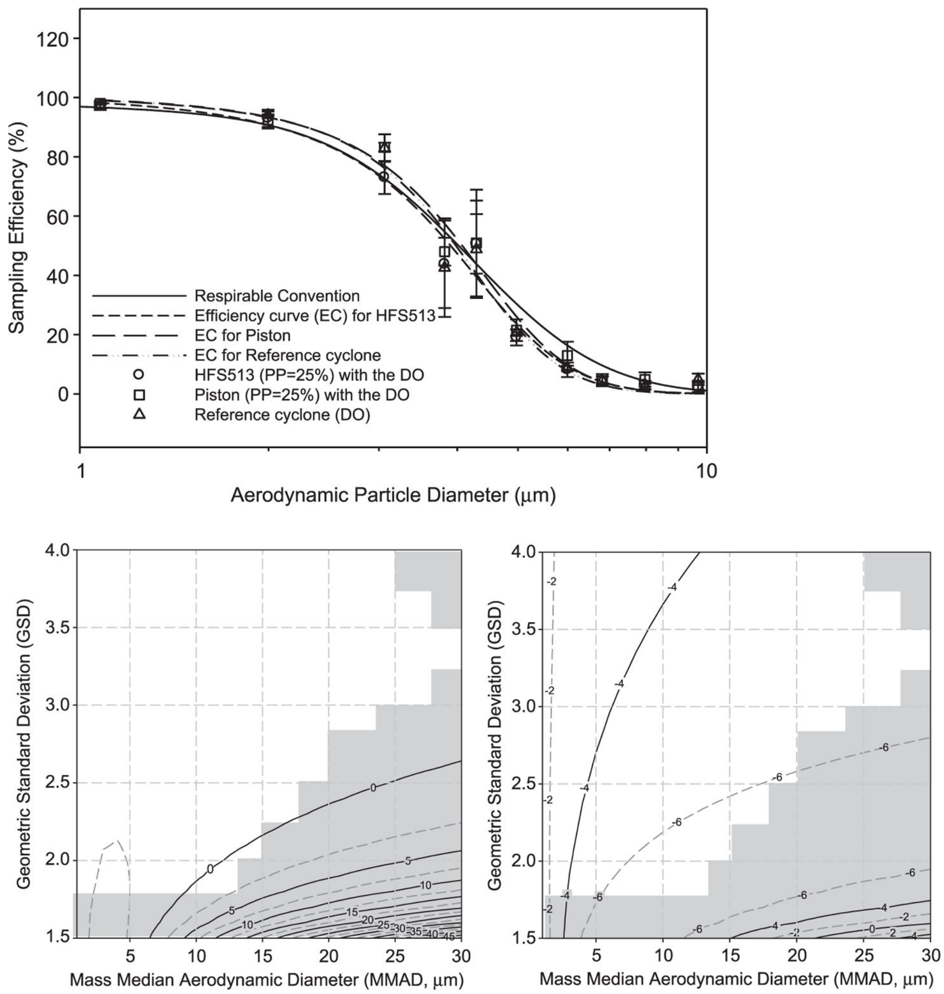

Fig. 6.

Sampling efficiency (SE) curves and bias maps for the HFS513 (PP = 25%) referenced to a pulse-free vacuum (left) and to a piston setup (right) (D_{50} of the reference DO cyclone = 3.97 μm with 50.3% SE).

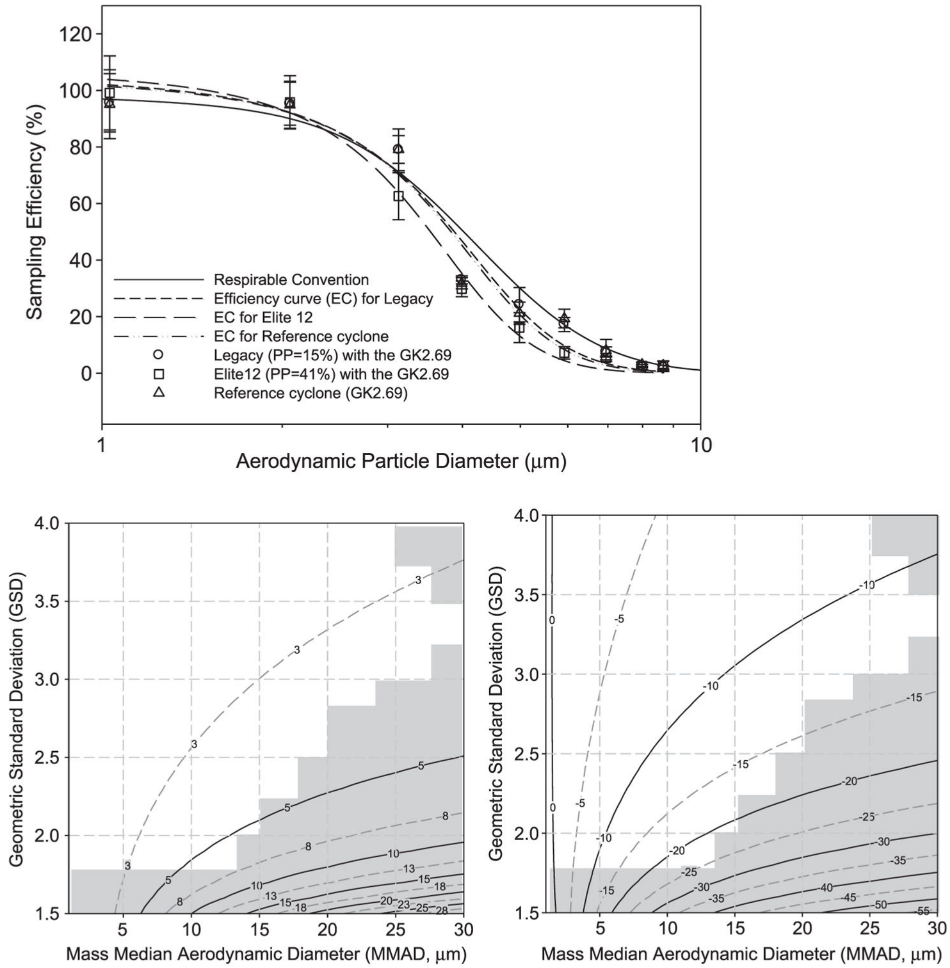

Fig. 7.
Sampling efficiency (SE) curves and bias maps for the GK2.69 cyclone when using the Legacy (left, PP = 15%) and Elite12 (right, PP = 41%) referenced to a pulse-free vacuum (D_{50} of the reference GK2.69 cyclone = 3.83 µm with 49.8% SE).

Table 1

Summary of the tested conditions and experimental study

Cyclone type	Pump ID	PP (%)[a]	Fundamental frequency (Hz)	PA (l/min)[b]	Normalized PA[c]	Sampling efficiency shift[d]
DO	Apex IS	5	36.6	0.18	0.10	No change
	HFS 513	25	34.6	0.80	0.47	No change
	GilAir5	30	36.6	0.98	0.58	Negative
	Elite5	56	24.4	1.48	0.86	Negative
	Basic5	70	24.4	1.71	1.00	Negative
GK 2.69	Legacy	15	34.6	1.17	0.27	No change
	Elite12	41	34.6	2.85	0.65	Negative

[a] $\mathrm{PP}=\frac{\left|\sqrt{\frac{1}{T}\int_0^T\left[f(t)-\overline{f}\right]^2 dt}\right|}{\overline{f}}$, where *f(t)* = volumetric flow rate with respect to time (l/min), $\overline{f}$ = mean volumetric flow rate over time *T* (l/min), *t* = time (s), and *T* = time period of pulsation (s).

[b] PA (pulsation amplitude) = the difference of peak and average flow.

[c] Normalized PA = PA divided by the average flow.

[d] Sampling efficiency shift of a cyclone using a pump model against the same cyclone type using a pulse-free flow.