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Evaluation of Pump Pulsation in Respirable Size-Selective Sampling: Part I. Pulsation Measurements

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Abstract

Pulsations generated by personal sampling pumps modulate the airflow through the sampling trains, thereby varying sampling efficiencies, and possibly invalidating collection or monitoring. The purpose of this study was to characterize pulsations generated by personal sampling pumps relative to a nominal flow rate at the inlet of different respirable cyclones. Experiments were conducted using a factorial combination of 13 widely used sampling pumps (11 medium and 2 high volumetric flow rate pumps having a diaphragm mechanism) and 7 cyclones [10-mm nylon also known as Dorr-Oliver (DO), Higgins-Dewell (HD), GS-1, GS-3, Aluminum, GK2.69, and FSP-10]. A hot- wire anemometer probe cemented to the inlet of each cyclone type was used to obtain pulsation readings. The three medium flow rate pump models showing the highest, a midrange, and the lowest pulsations and two high flow rate pump models for each cyclone type were tested with dust-loaded filters (0.05, 0.21, and 1.25 mg) to determine the effects of filter loading on pulsations. The effects of different tubing materials and lengths on pulsations were also investigated. The fundamental frequency range was 22–110 Hz and the magnitude of pulsation as a proportion of the mean flow rate ranged from 4.4 to 73.1%. Most pump/cyclone combinations generated pulse magnitudes >10% (48 out of 59 combinations), while pulse shapes varied considerably. Pulsation magnitudes were not considerably different for the clean and dust-loaded filters for the DO, HD, and Aluminum cyclones, but no consistent pattern was observed for the other cyclone types. Tubing material had less effect on pulsations than tubing length; when the tubing length was 183 cm, pronounced damping was observed for a pump with high pulsation (>60%) for all tested tubing materials except for the Tygon Inert tubing. The findings in this study prompted a further study to determine the possibility of shifts in cyclone sampling efficiency due to sampling pump pulsations, and those results are reported subsequently.

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Keywords

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

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INTRODUCTION

The effect of flow pulsation on the particle collection efficiency of personal sampling pumps was extensively studied in the 1970s by several researchers in the USA as part of an effort to improve sampling methodologies for respirable coal mine dusts. The mass of respirable dust collected with pumps generating pulsating flows was found to be less than that collected with steady but correspondingly equal mean flows (Anderson *et al*, 1971; Lamonica and Treaftis, 1972; Caplan *et at*, 1973; Blachman and Lippmann, 1974; McCawley and Roder, 1975). As a consequence of these studies, pulsation dampeners have been included in personal dust sampling units by the manufacturer to ensure a more constant flow. Furthermore, US 30 Code of Federal Regulations (CFR) Part 74 (CFR, 1974) administered jointly by the National Institute for Occupational Safety and Health (NIOSH) and the Mine Safety and Health Administration stated the allowable pump pulsation (PP) in Coal mine Dust Personal Sampler Units (CMDPSU's) as follows: '(i) The irregularity in flow rate due to pulsation shall have a fundamental frequency of not less than 20 Hz. (ii) On and after July 1,1974 the quantity of respirable dust collected with a sampler unit shall be within 5 percent of that collected with a sampling head assembly operated with nonpulsating flow.'

Bartley *et at.* (1984) revisited this issue by investigating PPs and their effects on the 10-mm nylon cyclone, also known as the Dorr-Oliver (DO) cyclone. Three types of sampling pumps were tested, the MSA Model G, the Bendix Mcronair II, and the DuPont P-2500 pumps, all of which had pulsation dampeners. A resonance was clearly observed due to the combined effect of the tubing between the cyclone and the pump, the filter, and the filter cassette, in which the ratio of fluctuating amplifications in the section of tube between the pump and the cyclone ranged between 1 and 2 for the frequency range of 0–250 Hz. The predicted bias of the cyclone collection efficiency was negligible for the MSA Model G and Bendix Mcronair II pumps at both 2.0 and 1.2 l $\min^{-1}$ and for the DuPont P-2500 pump at 2.0 l $\min^{-1}$, while the bias was in the order of −20% for the DuPont P-2500 pump at 1.2 l $\min^{-1}$. Berry (1991) also observed penetration shifts from the comparison of sampling efficiencies of the SIMPEDS cyclone without pulsation and with pure sinusoidal pulsations at a frequency range of 20–280 Hz; a positive penetration shift was observed for large particles (>5 μm) at low frequencies and increased with pulsation amplitude, while the penetration shift was negative and decreased with increasing amplitude at higher frequencies. Recently, Cornelissen (2008) evaluated several pumps from each of three different manufacturers equipped with flow stabilizers and reported that all pumps exceeded the maximum allowable pulsation (>10%), recommended by a recent European Standard (see next paragraph).

Different types of pumps and manufacturers are listed by Monteith and Rubow (2001) and Monteith and Leong (2009). An Internet search (June 2009) returned 32 portable sampling pumps, from several manufacturers, ranging up to 5–6 l $\min^{-1}$. Most of these personal sampling pumps have a diaphragm pulsation dampening mechanism, and, in addition, some sampling pumps have an electronic sensor to provide feedback to maintain a constant mean airflow. Consensus technical standards for testing the performance of sampling pumps do not exist in the USA except for a few general requirements such as intrinsic safety (Monteith and Leong, 2009). The European Standard EN 1232–1997 (Workplace atmospheres - Pumps for personal sampling of chemical agents - Requirements and test methods) specifies requirements for testing battery-powered pumps used for personal sampling of airborne contaminants in the workplace (CEN, 1997). In addition, the EN 12919–1999 (Workplace atmospheres - Pumps for the sampling of chemicals agents with a volume flow rate over 5 l min^{-1} - Requirements and test methods) specifies requirements for testing sampling pumps with a flow rate >5 l min^{-1} (CEN, 1999). The EN 1232–1997 Standard listed PP as one parameter to be tested for personal sampling of airborne particles (defined as type P pumps), stating ‘For type P pumps the pulsation shall not exceed 10% of the flow rate.’ That same 10% requirement also appears in the EN 12919–1999 Standard (CEN, 1999). However, manufacturers have not published data to show that this requirement is being met. A new work item for a consensus international standard for sampling pump performance has been introduced through the International Organization for Standardization (ISO). The ISO Committee responsible for the standard is discussing whether the test in the European Standards is appropriate for an ISO Standard. Data are lacking with regard to flow rate pulsation and sampling performance of sampling pumps in current usage and would be beneficial in informing Committee discussions.

This study evaluated PPs generated by 13 models of personal sampling pumps used for respirable size-selective sampling of aerosols. Two aims were established as the goal of this study. Aim 1 was to characterize PPs as measured at the inlet of seven widely used cyclones. The European Standards suggested pulsation measurements at 20 cm upstream of a resistor, which replaces an aerosol sampler. This study performed pulsation measurements at the inlet of a cyclone because it is more representative of a real-world sampling train. The findings of Aim 1 are reported in this article. Aim 2 was to measure changes in collection efficiency and to correlate these changes with the pulsations measured in Aim 1. The concluding article of this two part series reports the findings from the Aim 2 research.

MATERIALS AND METHODS

Pulsation measurements at the inlet of cyclone without filter loadings

A total of 13 personal sampling pumps, 11 medium (up to 5 or 6 l min^{-1}) and 2 high (up to 10 or 15 l min^{-1}) volumetric flow rate pumps, were selected. The selection process consisted of those models already in use in-house plus a few others selected from the overall population found by an Internet search to ensure that at least one pump was represented from each manufacturer found by that search (Table 1). Specific models chosen were those thought to be widely used by occupational hygienists, although exact sales numbers were not available to confirm this. All pumps were purchased on the open market. Although three of the medium volumetric flow rate pumps (HFS513 MG5P, and SP730) are no longer available in the market, they were included because these pumps are still in use in-house and elsewhere. The seven cyclone models used are listed in Table 2. These are representative of the majority of cyclones available commercially.

It is impossible to place a hot-wire probe between a vortex chamber and the filter as doing so would alter the performance of the cyclone. An alternative placement of a probe is in front of the cyclone inlet, as in the previous study by Bartley *et al.* (1984), which reported that no change of aerosol penetration would result from the presence of such a probe at the inlet of a DO cyclone. Mounting is critical to ensure no modulation of the measurement is caused by movement or vibration of the probe. Clamping or cementing are both acceptable methods. For initial testing, three cyclones per cyclone type were tested to determine within- and between-cyclone variation per cyclone type with respect to PPs. For this preliminary test, a probe (Model Type 55P11; Dantec Dynamics A/s, Skovlunde, Denmark) was held in a custom clamp secured to a support stand (Fig. 1, left) rather than being cemented in place. The custom clamp was then adjusted to bring the probe in front of and within 1 mm of the cyclone inlet, the set-up calibrated, and care taken to assure that no accidental bumping or incidental vibration was introduced throughout the experiments. The cyclones of each type were ordered by pulsation magnitude, the cyclone with the median value was selected, and a probe was permanently mounted in front of the inlet of that cyclone using a custom bracket. Figure 1 (right) shows an example of a mounting bracket. Customized brackets were necessary because the cyclones did not present geometries compatible with direct mounting of the probes.

A calibration curve for each probe was prepared by measuring the response voltage at the output of the miniature constant temperature anemometer (CTA) for nine different nominal flows (0.33,0.61,1.25,2.50, 5.00, 7.50, 10.0, 15.0, and 20.0 l min^{-1}). Flow was generated by a laboratory vacuum and was set using an adjustable needle valve to the desired flow rate as indicated by DryCal® DC-Lite (BIOS International Corporation, Butler, NJ, USA). The analog output voltage from the miniature CTA was digitized using National Instruments (Nl) Corporation (Austin, TX, USA) equipment. The CTA jumpers were configured to provide a 3-kHz low-pass filter to prevent aliasing. The output signal was measured using a data acquisition card programmed to acquire 200 000 samples per second. The data were then exported to SigmaPlot® (Systat Software Inc., San Jose, CA, USA) to obtain the coefficients of a cubic polynomial equation. Each developed equation was then programmed to the data acquisition card to convert the output voltage readings to the corresponding flow rates. Once the converted flow rates were gathered; PP was calculated using the following equation (CEN, 1997):

$$PP=\frac{|\sqrt{\frac{1}{T}\int_0^T\left[f(t)-\overline{f}\right]^2dt}|}{\overline{f}}\qquad(1)$$

where $f(t)$ - volumetric flow rate with respect to time (l min^{-1}), f - mean volumetric flow rate over time T (l min^{-1}), t - time (s), and T = time period of pulsation (s). In addition, a fundamental frequency was calculated using a fast Fourier transform (FFT) algorithm in Excel (Microsoft Inc., Redmond, WA, USA). The total number of runs was 495 for the medium volumetric flow rate pumps (11 pump types × 3 pumps/ type × 5 cyclone types × 3 replicates = 495) and 36 for the high volumetric flow rate pumps (2 pump types × 3 pumps/ type × 2 cyclone types × 3 replicates = 36). Figure 2 shows an example of the test set up for pulsation measurements.

For the Aluminum and GK2.69 cyclones, optimum flow rates of 2.2 and 4.4 l $\min^{-1}$, respectively, were used instead of those recommended by the manufacturers so that testing would follow the American Conference of Governmental Industrial Hygienists/ISO/Comite Européen de Normalisation (CEN) respirable convention (Lee *et al*, 2010). For the FSP-10 cyclone, both 10.0 l $\min^{-1}$ (manufacturer recommended) and 11.2 l $\min^{-1}$ (optimized flow rate by Lee *et al*, 2010) were tested. Also, in order to minimize possible variation due to other factors such as filter type and tubing length, only one type of filter, a polyvinyl chloride (PVC) filter with 5-μm pore size, and an aluminum rigid tubing 91.4 cm long with 0.64 cm inner diameter (ID) were used in this study. A 91.4 cm long tubing was selected in accordance with US 30 CFR Part 74 (1974) for CMDPSUs. Preliminary observations revealed that air currents from ventilation in the laboratory, as well as from personnel moving around or opening and closing doors, sometimes modulated the data. Thus, measurements were isolated from these air currents by housing the cyclone under test, the hot-wire probe, the interconnecting cable, and the miniature CTA within the chamber shown in Fig. 2.

Pulsation measurements at the inlet of cyclone with filter loadings

Flow fluctuations from a factorial combination of five pump models, three loading amounts, and seven cyclone types were obtained at the inlet of each cyclone type to compare pulsations with and without dust loadings (Table 3). Three medium flow rate pumps showing the smallest (Apex IS), a midrange (HFS513), and the largest (Basic5) pulsations and two high flow rate pumps were selected based on the results of the previous section. For filter loads, three samples of respirable silica dust (loading amount: 0.05, 0.21, and 1.25 mg) collected on PVC filters from a field survey but not used for further sample analyses (e.g. filter digestion process) were used. The same experimental set-up in Fig. 2 was used except for switching the clean filter to a loaded filter. For each condition, three replicates were performed. The pressure drop across the cyclone, the filter installed in the cyclone, and the tubing connected to the pump was measured using a differential pressure gauge to determine back pressure changes with and without filter loadings. The pressure drop in the medium flow setups was measured with MK III handheld digital manometers (models 475–00-FM and 475–0-FM; Dwyer Instruments Inc., Michigan, IN, USA) and in the high flow setups with a C9503 pressure meter (Comark Ltd, Stevenage Hertfordshire, UK).

Pulsation measurements based on various tubing lengths and tubing materials

The influence of tubing material and length upon pulsations was investigated by NIOSH in the USA and by the Institut fur Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung [Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA)] in Germany. NIOSH tested a full factorial combination of five tubing materials (Tygon® SE-200 inert, Tygon®R3603, PVC, aluminum, and latex rubber), three different lengths with 0.64 cm ID, two pump models (Apex IS and Basic5), and one Higgins-Dewell (HD) cyclone. The Tygon® SE-200 inert tubing has an inner layer that can be easily detached from the body of the tubing. The elasticity of the Tygon® SE-200 inert tubing material is less than the Tygon® R3603. Using the US 30 CFR Part 74 (1974) for CMDPSU's length of 91.4 cm as a baseline, we halved (45.7 cm) and doubled (183 cm) it to provide the test lengths. The test set-up was the same as that shown in Fig. 2.

The test set-up at the IFA was different (Fig. 3). Instead of measuring pulsations at the inlet of the cyclone, IFA obtained measurements upstream of the cyclone, 20 cm to the FSP-10 cyclone and 10 cm to the HD and GK2.60 cyclones. The European Standards recommend pulsation measurements at 20 cm upstream of a flow resistor. Although the tubing lengths at IFA were not always as specified in the European Standards, little difference (<3% difference in pulsation magnitude) was found using a HFS513 pump connected to the HD cyclone, which confirmed a negligible difference between the two tubing lengths. Combinations of two tubing materials (PVC and silicone), three tubing lengths (45.7, 91.4, and 183 cm) with 0.60 cm ID, five pump models (Apex IS, Basic5, HFS513, Elite 12, and Legacy), and three cyclone types (HD, GK2.69, and FSP-10) were tested by IFA. With 45.7 cm of tubing connecting a flow resistor to the pump, additional pulsation data were recorded with the flow resistor (Swagelok needle valve type JN R, brass-screwed-Bonnet needle valve, 2.54 cm) adjusted to 0.75 kPa as given in the EN 1232 method. The hot-wire anemometer was positioned at 10 cm upstream of the resistor. The hot-wire anemometer (mounted inside a tube, 6 mm ID, 80 mm length, customized from Dantec Dynamics A/s) analog output was amplified and digitized by a NI computer card. The digitized signals from a 10-s pulse measurement were converted into pulsations after being processed by equation (l) using Dasy Lab software from NI.

RESULTS

Pulsation measurements at the inlet of cyclone without filter loadings

Each individual cyclone showed <2% variation in PP for repeated runs. Between-cyclone variation was <10% per cyclone type except 12% variation of the GS-3 cyclone and 13% variation of the GK2.69 cyclone.

Table 4 shows pulsations for the combinations tested, average value of three pumps for each pump model. Overall, most sampling pumps generated pulsations >10% (range 4–73%), exceeding the allowable pulsation specified in the EN 1232–1997 (CEN, 1997) and EN 12919–1999 (CEN, 1999). Note, however, that the hot-wire probes were positioned in front of the inlet of the cyclones, as shown in Fig. 3, as opposed to the set-up called for in both EN Standards. Only the Apex IS pump showed PPs < 10% with all tested cyclones. The SP730 pump showed the same except when used with the DO cyclone. The Gilian5000 showed <10% PP only when used with the DO and GS-1 cyclones. When the nominal flow rates were similar (e.g. <2.75 l min^{-1} for the DO, GS-1, Aluminum, HD, and GS-3 cyclones), the pulsations were not substantially different. Figure 4 illustrates an example of pulse magnitudes measured at the inlet of the DO cyclone connected to each pump model. Similar results were observed with the GK2.69 and FSP-10 cyclones at high flow rates. Pulsation magnitudes for the FSP-10 cyclone with the Elite 12 running at 11.2 l min^{-1} could not be measured due to instability of the nominal flow rate.

Pulsations generated by some sampling pumps (e.g. the PCXR8, GilAir5, and HFS513; Fig. 4) are of different shape from those of other pumps, and it is unknown whether pulse shape is an important factor affecting sampling efficiency of respirable particles.

All the pump models generated frequencies >20 Hz minimum required by US code 30 CFR Part 74 (1974). For the combinations shown in Table 5, the fundamental frequencies between pump models were considerably different, ranging from 22 to 110 Hz. Overall, a linear relationship between the fundamental frequency for each pump model and the nominal flow rate was observed. Linear regression revealed that the slope was dependent upon pump model. The pulsation amplitude as a percentage of the mean flow rate was similar for all tested cyclone types per pump model. For the medium flow rate pumps (i.e. covering five cyclone types per pump model), average amplitude percent to the mean flow increased with increasing PP, while no trend was observed between the average fundamental frequency and PP (Fig. 5).

Pulsation measurements at the inlet of cyclone with filter loadings

As shown in Fig. 6, the pulsation magnitudes for the DO, HD, Aluminum, and FSP-10 cyclones were not notably different for the clean and particle-loaded filters. For the GS-1 and GS-3, the pulsations changed with different filter loading, but no patterns were observed. For example, the highest pulsation was observed at 1.25 mg loading for the GS-1 and at 0.21 mg loading for the GS-3 cyclone. Also, all average frequencies were >20 Hz except when filter loading was 1.25 and 0.05 mg for the combination of the DO cyclone with the Basic5 pump (18.3 Hz for both). Like the pulsation magnitudes, the pulse frequencies showed no patterns among the different loading amounts.

Table 3 shows the pressure drops. Each value represents an average of three pump models for the medium volumetric flow rate pumps and two pump models for the high flow rate pumps (except for the FSP-10 running at 11.2 l min-l). Back pressure increased with filter loading and flow rate, but was not considerably different among pump models per cyclone type for each filter loading (results not presented).

Pulsation measurements with different tubing materials and tubing lengths

Figure 7 shows PPs at the inlets of a HD and a GK2.69 cyclone with various tubing materials and lengths. No change in pulsations was observed for the pump that had the lowest pulse amplitudes, the Apex IS. In contrast, for the Basic5 pump (PP > 60%), the pulsations when using 45.7- and 91.4-cm Tygon Inert tubing and 183-cm latex rubber tubing were lower than those of other combinations, while 45.7-cm Tygon R3606 showed 1.2 times higher pulsation than when using the other materials of the same length. The rigidity of tubing materials appeared to have little effect on pulsation. Overall, pulsations with 183-cm tubing length were always lower than when using 45.7 and 91.4 cm tubes regardless of tubing material. The pulsation with a flow resistor was −20% lower than that with the HD cyclone when using the Basic5 pump, and about the same when using the Apex IS pump. A similar pattern was observed for the GK2.69 cyclone. For the Legacy pump (PP = 14%), pulsations were similar regardless of tubing material and length. The Elite 12 (PP = 41%)

showed no effect of tubing material and with two tubing lengths (45.7 and 91.4 cm), whereas 183 cm always showed lower pulsations compared to the other two lengths.

DISCUSSION

PPs at the inlet of cyclone (with and without filter loadings)

In this study, 48 out of 59 combinations of pump and cyclone showed >10% pulsation. Bartley *et al*. (1984) reported less fluctuation when the nominal flow rate for the MSA Model G and Bendix Micronair II pumps was reduced from 2.0 to 1.2 l min-1. However, our study did not demonstrate the same pattern. When the nominal flow rates of respirable cyclones were similar (e.g. between 1.7 and 2.75 l min-1), the pulsation magnitudes were similar for all cyclone types per pump model (<5% standard deviation [SD]) but were substantially different between pump models for each cyclone type (i.e. SD ranging 17–21% per cyclone type). Overall, the findings of this study clearly indicate that PPs were highly dependent upon pump model alone, not cyclone type. In addition, because some sampling pumps showed notably different pulsation shapes compared to other pump models, it may further be necessary to determine how pulsation shape affects respirable particle collection efficiency.

Both EN 1232–1997 (CEN, 1997) and EN 12919–1999 (CEN, 1999) recommended 10% as an acceptable pulsation, but it is not clear how this 10% limit was derived, and no scientific basis was reported. As described previously, pulsation measurements in this study were obtained with a different procedure than that provided in the EN Standards. Both EN Standards specify using a flow resistor instead of a cyclone sampler and require pulsation measurement at a point 20 cm upstream of the resistor. For the medium flow rate pumps, the flow rate is adjusted to 2.0 l min-1 with a pressure drop of 0.75 kPa. For the high flow rate pumps (i.e. >5.0 l min-l), the flow rates are adjusted to a mean value of the nominal flow rate range and the flow resistance to the lower limit of the nominal range of back pressure for this flow rate. In this study, we used several cyclone types and fixed a probe at the inlet of each cyclone type to characterize pulsation measurements, as suggested by Bartley *et at*. (1984). This set-up uses a real-world sampling train (i.e. a cyclone and filter in a cassette), none of which appear in the EN methods. It was observed that pulsation magnitude (−20%) using a flow resistor was lower than pulsation magnitude measured with the HD cyclone for a pump generating high pulsations (>40%). This difference might be due to the different characteristics of a cyclone (including a filter and filter cassette) compared to flow resistors. It is also expected that different types of flow resistor would generate different pulsations. Since this observation was based on limited test conditions, a comprehensive study would be necessary to determine the relationship of pulsations (e.g. a correction factor between resistor and cyclone) between the two procedures, addressing also any dependence on the volume inside the sampling train. This complexity was beyond the scope of this research.

US 30 CFR Part 74 (1974) for CMDPSU’s introduced two criteria for the allowable pulsation. The first criterion mandated the fundamental frequency of pulses to be >20 Hz. All frequency measurements in this study passed this criterion. The second criterion is that the mass collected by a sampler using a pump as a vacuum source be within 5% of that which would be collected by the same sampler using a steady and nonpulsating vacuum, both samplers exposed to the same concentration of particulates, operating at the same mean flow, and for the same duration. Although the second part of this study does examine collection performance, the specific test requirement for this regulation, which has only limited application to the workplace, involves testing 10 units, which is beyond the resources available to this study.

No pattern was observed when comparing pulsations with and without dust loadings. Berry (1991) reported that 8 mg of respirable dust loading on a filter (i.e. corresponding to l0 mg m^{-3} for 8-h sampling) had little effect on the pulsations. Although the results of this study and Berry's study are similar, the lack of detailed information (e.g. test set-up and no provision of data) reported by Berry (1991) precludes any meaningful comparison. The pressure drops across all filters used in this study (up to 1.25 mg loading) ranged 0.76–1.35 kPa for the medium volumetric flow rate pumps and 1.92–3.33 kPa for the high volumetric flow rate pumps. Currently, the EN 1232–1997 (CEN, 1997) recommends setting the flow resistor pressure drop setting at 0.75 kPa with 2.0 l min-1 flow rate for pumps whose nominal flow rate is up to 5.0 l min-1. The findings of this study suggest that one test condition (0.75 kPa resistance with 2.0 l min-1) might not be sufficient for a complete PP test. Thus, adding one or two additional resistances in the test condition is recommended.

PPs due to different tubing materials and tubing lengths

No effects on pulsation resulting from different tubing materials and tubing lengths were observed for pumps showing < 15% pulsations (Apex IS and Legacy pumps). For pumps showing higher pulsations (the Basic5 and Elite 12 pumps), the results suggest that tubing material had less effect on the pulsation than tubing length. The comparison of pulsations among different tubing materials did not show considerable differences except for three setups: 45.7 and 91.4 cm Tygon Inert tubing and 45.7 cm Tygon R3603 tubing materials. The reason for these differences was not clear. The rigidness of tubing materials seemed to have no effect on the fluctuations. One interesting result is that even though the test conditions between the NIOSH and IFA were different, the pulsations measured using PVC tubing material were not different. This observation seems to suggest that different positions of the hot-wire anemometer probe would give similar results. However, because this observation is based on only one tubing material, additional test using various tubing materials might be required.

Berry (1991) compared 50- and 100 -cm tubing of unreported composition and observed no change in penetration while using five diaphragm sampling pump types (frequency range 30–80 Hz). Similar results were observed in this study for tubing lengths <100 cm. For all the 183-cm tube tests, pulsation in most cases was reduced by ~10%. Perhaps the reduction represents damping as air volume in the tube increased with length, but which only becomes noticeable once the length nearly doubles from 91.4 cm. Overall, it seems reasonable to use a 91.4-cm (±10%) tubing length for field survey work because the pulsation measurements using different tubing materials were not considerably different from those obtained for 45.7 cm. Furthermore, the US 30 CFR Part 74 and other US national and international regulations recommend similar lengths for personal sampling when connecting a pump positioned on a belt with a sampling head positioned in the breathing zone.

CONCLUSIONS

The findings of this study indicate that pump fluctuations at the inlet of each of the cyclone types were considerably different across pump models (~80% showing >10% pulsation). Pulse magnitudes were similar for the clean and three dust-loaded filters for the DO, HD, and Aluminum cyclones, and no pattern was observed for the other cyclone types. Also, the results revealed that tubing material had less effect on pulsations than tubing length.

Tsai and Shih (1995) stated that ‘In general, particle collection efficiency decreases with increasing pump pulsations, aerodynamic diameter, or pulsation frequency’ The next phase of this study was designed to determine whether PPs do indeed cause a significant shift in sampling efficiency and, if so, is there an upper limit for PP that is acceptable without invalidating collection and monitoring? In addition, some pump models showed different pulsation shapes suggesting a further study may be necessary to determine the effects of pulse shape on sampling efficiency. To answer these questions, an extended study using monodisperse particles was undertaken (Aim 2). The findings are reported in the same issue of this journal (Lee *et al*., 2013). The findings of this Aim 1 and Aim 2 studies should form a basis for defining acceptable PPs and for developing or revising consensus technical standards.

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Figure 1.

Hot-wire anemometer probes: placed near the inlet of a cyclone (left); held in a custom bracket and cemented onto a cyclone (right).

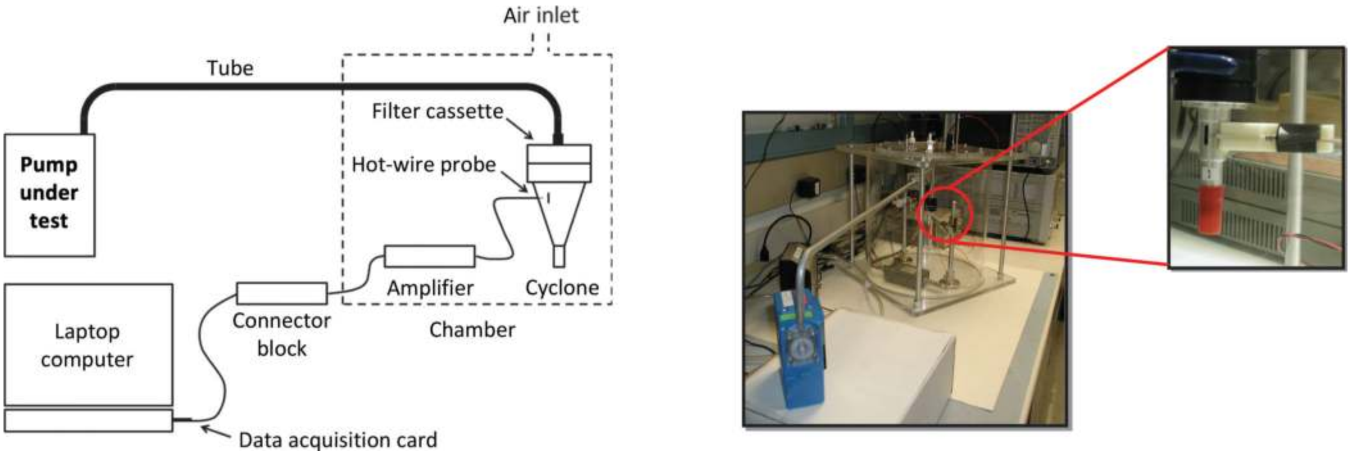

Figure 2.
Experimental set-up (NIOSH).

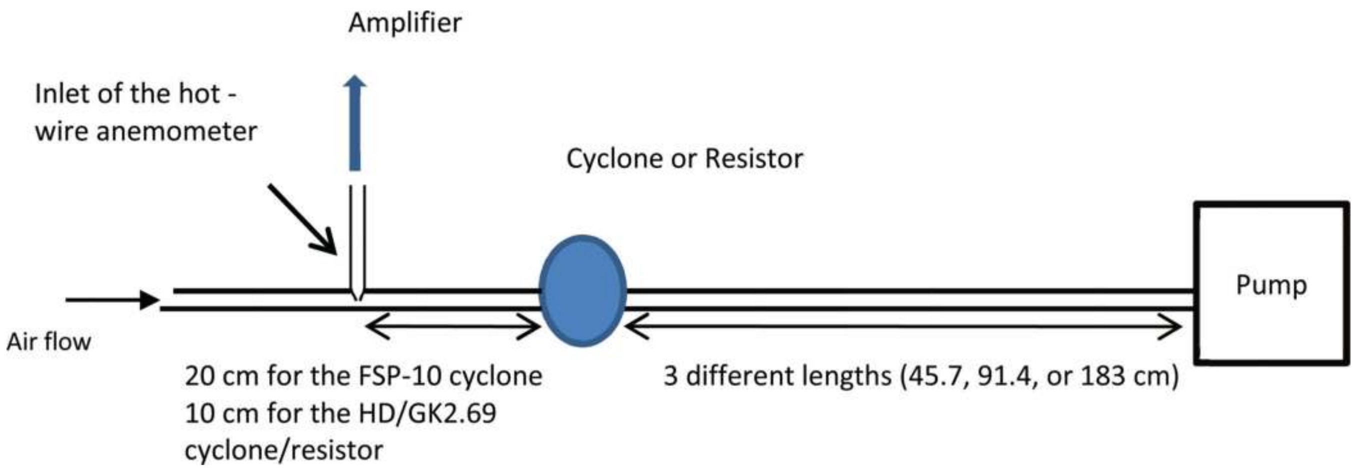

Figure 3.
Experimental set-up for pulsation measurements (IFA).

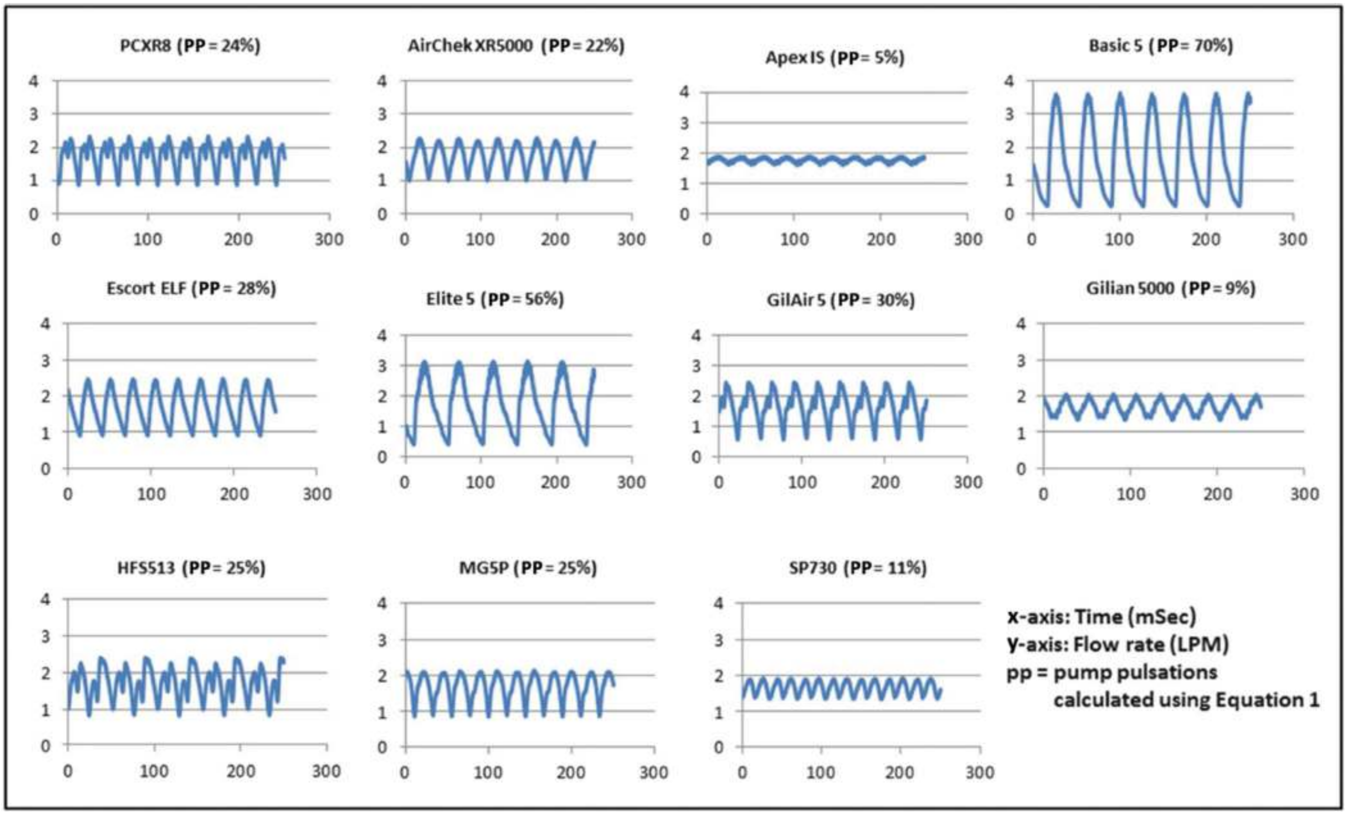

Figure 4.

Example of PPs (medium volumetric flow rate pumps connected to the DO cylcone).

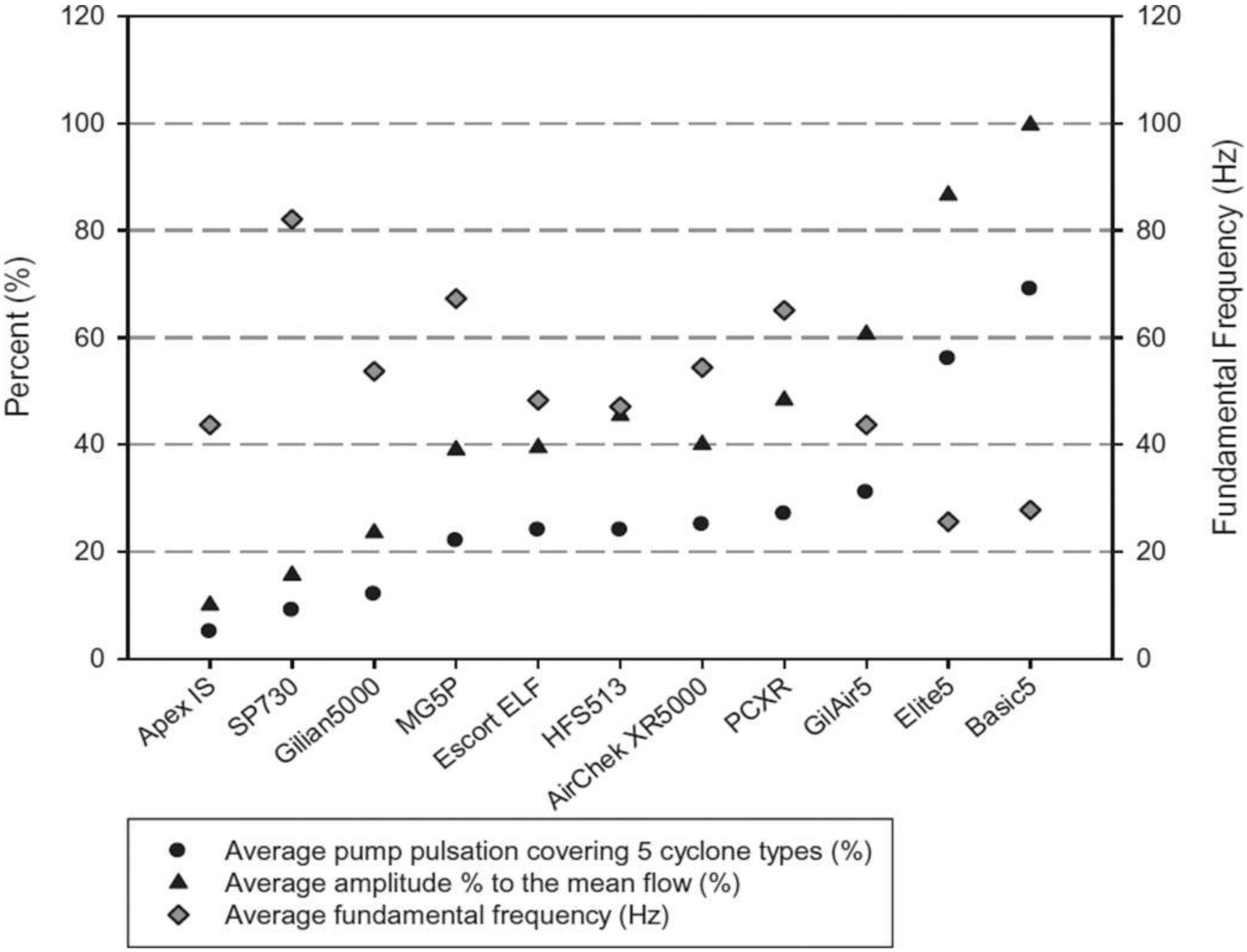

Figure 5.

Average PP (%), fundamental frequency of pulses (Hz), and average amplitude of pulses compared to the associated mean flows (%) for the medium volumetric flow rate pumps.

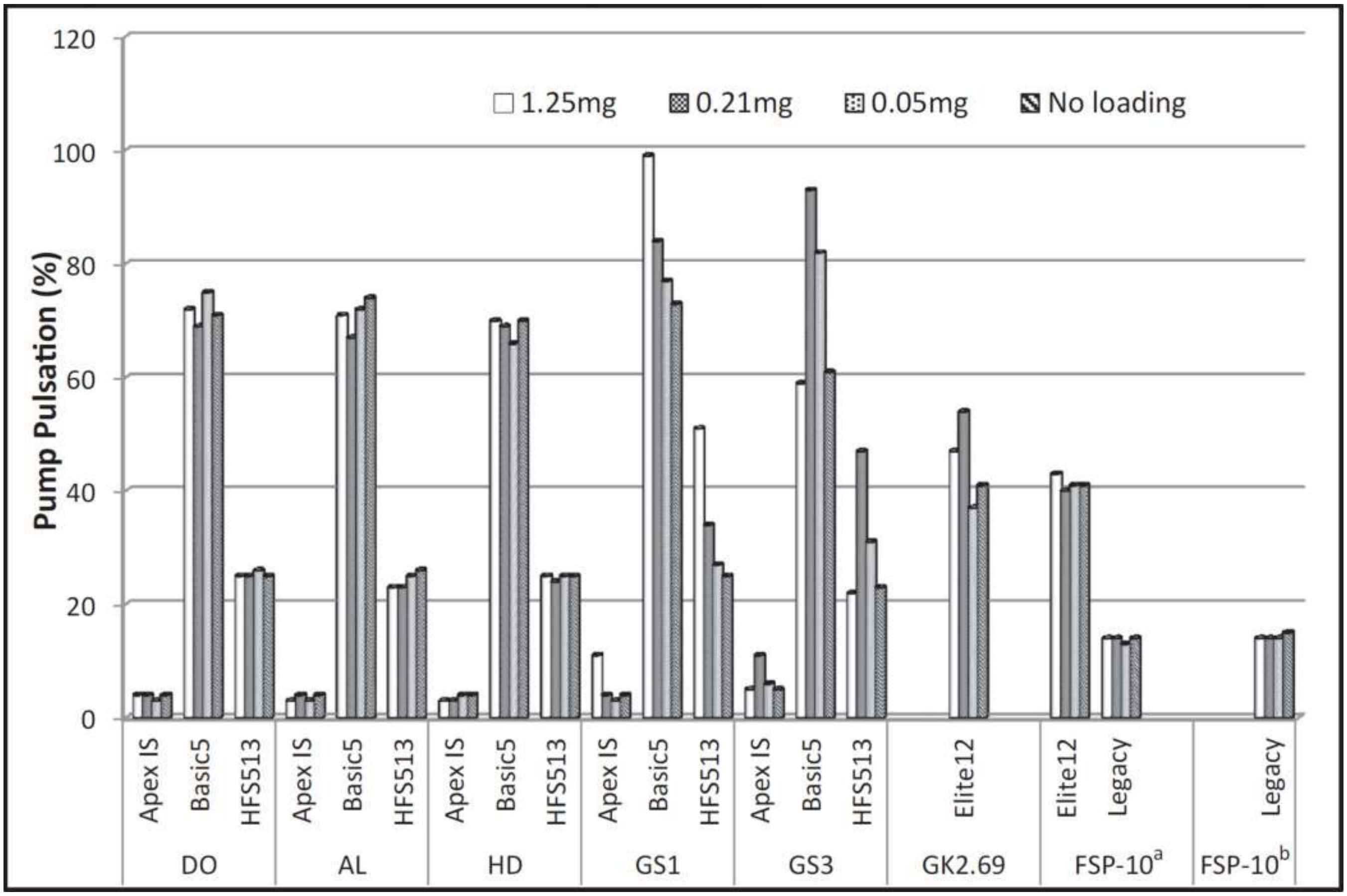

Figure 6.

Comparison of PPs with different filter loading (Note that the nominal flow rate for the FSP-10^a and FSP-10^b was 10 and 11.2 l min^{-1}, respectively.).

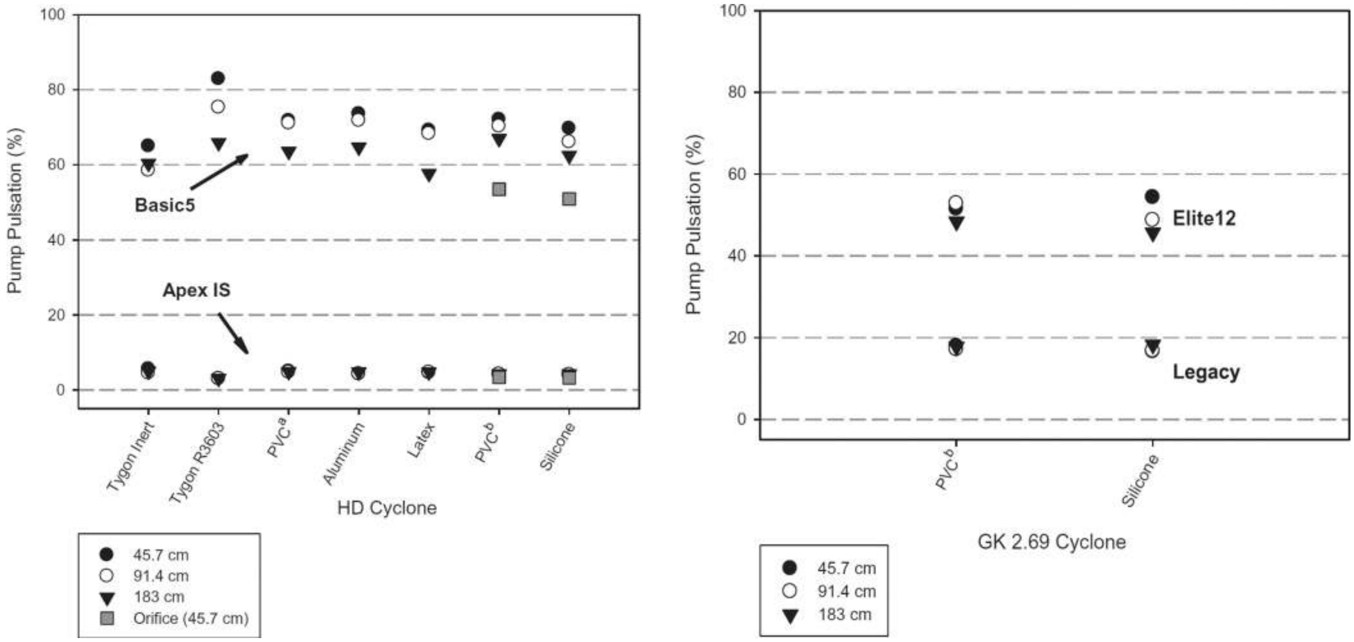

Figure 7.

PPs with various tubing materials and lengths (PVC^a: pulsation measurements by NIOSH; PVC^b: pulsation measurements by IFA). Note that the two square solid dots for the Basic5 and Apex IS are pulsations with a flow resistor.

Table 1

Selected personal sampling pumps

Pump		**Manufacturer**	**Flow rate range (l min^{-1})**
Medium volumetric flow rate pumps (n = 11)	PCXR8	SKC Inc., Eighty Four, PA, USA	0.005–5
	AirChekXR5000	SKC Inc.	0.005–5
	Apex IS	CASELLA, Amherst, NH, USA	0.005–5
	Basic5	A.P. Buck Inc., Orlando, FL, USA	0.005–5
	Escort ELF	MSA The Safety Company, Pittsburgh, PA, USA[a]	up to 3
	Elite5	AP. Buck Inc.	0.005–6
	GilAir5	Sensidyne, LP, Clearwater, FL, USA	0.001–5
	Gilian5000	Sensidyne, LP	0.02–5
	HFS513[b]	Sensidyne, LP	0.001–5
	MG5P[b]	AMETEK, Largo, FL, USA	up to 5
	SP730[b]	TSI Inc., Shoreview, MN, USA	up to 3
High volumetric flow Rate pumps (n = 2)	Elite 12	AP. Buck Inc.	3–12
	Legacy	SKC Inc.	5–15

[a] Now available from Zefon International Inc., Ocala, FL, USA.

[b] Product discontinued but still widely used in practice.

Table 2

Cyclones selected for pulsation measurements

Cyclone type	Recommended flow rate (l min $^{-1}$)	Manufacturer
10-mm nylon (or DO)	1.7	Sensidyne, LP, Clearwater, FL, USA
GS-1	2.0	SKC Inc.
Aluminum	2.5 (2.2)[a]	SKC Inc.
HD	2.2	BGI Inc., Waltham, MA, USA
GS-3	2.75	SKC Inc.
GK2.69	4.2 (4.4)[a]	BGI Inc.
FSP-10	10(ll.2)[b]	GSA Messgeratebau GmbH, Neuss, Germany

[a] Instead of the recommended flow rate by the manufacturer, optimum flow rate defined by Lee *et al*. (2010) was used.

[b] Both 10 and 11.2 l min $^{-1}$ were tested.

Table 3

Pressure drop measurements[a] (unit: kPa)

Pump model		Cyclone type	Nominal flow rate (l min^{-1})	Filter loading (mg)			
				Clean	0.05	0.21	1.25
Medium flow Rate pumps	Apex IS, Basic5, and HFS513	DO	1.7	0.76	0.80	0.83	0.88
		GS-1	2.0	0.85	0.89	0.93	0.98
		Aluminum	2.2	0.92	0.97	1.01	1.07
		HD	2.2	0.89	0.97	1.03	1.06
		GS-3	2.75	1.18	1.24	1.29	1.35
High flow rate pumps	Elite 12 and Legacy	GK2.69	4.4	1.92	2.00	2.09	2.23
		FSP-10	10.0	2.20	2.27	2.66	3.04
		FSP-10[b]	11.2	2.55	2.55	3.09	3.33

[a] Note that each back pressure measurement is an average value of three pump models for the medium volumetric flow rate pumps and two pump models for the high volumetric flow rate pumps.

[b] Only the Legacy pump was used for the back pressure measurements.

Table 4

Measured PPs (%) for all combinations of pumps and cyclones

Cyclone type	Pump models											
	PCXR8	**AirChek XR5000**	**Apex IS**	**Basic5**	**Escort ELF**	**Elite5**	**GilAir5**	**Gilian 5000**	**HFS513**	**MG5P**	**SP730**	**Elite12**	**Legacy**
DO	24	22	5	70	28	56	30	9	25	25	11		
Aluminum	28	26	4	73	24	57	32	14	26	23	8		
HD	28	26	4	71	24	57	32	12	25	23	9		
GS-1	26	22	4	72	24	60	30	10	24	22	9		
GS-3	29	26	5	61	19	51	31	15	22	20	7		
GK2.69												41	15
FSP-10[a]												41	14
FSP-10[b]													15

[a] Flowrate is 10 l min^{-1}

[b] Flow rate is 11.2 l min^{-1}.

Table 5

Fundamental frequency (Hz) using the FFT method.

Cyclone type	Pump models												
	PCXR8	AirChek XR5000	Apex IS	Basic5	Escort ELF	Elite5	GilAir5	Gilian 5000	HFS513	MG5P	SP730	Elite12	Legacy
DO	48	39	37	24	37	24	37	37	35	47	56		
Aluminum	69	58	43	28	50	26	45	61	49	72	88		
HD	61	59	43	27	47	24	39	55	48	73	85		
GS-1	64	47	43	26	43	22	43	49	45	61	73		
GS-3	83	69	53	33	65	31	55	67	59	83	109		
GK2.69												35	35
FSP-10[a]												90	94
FSP-10[b]													110

[a] Flowrate is 10 l min^{-1}

[b] Flow rate is 11.2 l min^{-1}.