Parallel particle impactor – novel size-selective particle sampler for accurate fractioning of inhalable particles

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Abstract. Adverse health effects due to exposure to airborne particles are associated with particle deposition within the human respiratory tract. Particle size, shape, chemical composition, and the individual physiological characteristics of each person determine to what depth inhaled particles may penetrate and deposit within the respiratory tract. Various particle inertial classification devices are available to fractionate airborne particles according to their aerodynamic size to approximate particle penetration through the human respiratory tract. Cyclones are most often used to sample thoracic or respirable fractions of inhaled particles. Extensive studies of different cyclonic samplers have shown, however, that the sampling characteristics of cyclones do not follow the entire selected convention accurately. In the search for a more accurate way to assess worker exposure to different fractions of inhaled dust, a novel sampler comprising several inertial impactors arranged in parallel was designed and tested. The new design includes a number of separated impactors arranged in parallel. Prototypes of respirable and thoracic samplers each comprising four impactors arranged in parallel were manufactured and tested. Results indicated that the prototype samplers followed closely the penetration characteristics for which they were designed. The new samplers were found to perform similarly for liquid and solid test particles; penetration characteristics remained unchanged even after prolonged exposure to coal mine dust at high concentration. The new parallel impactor design can be applied to approximate any monotonically decreasing penetration curve at a selected flow rate. Personal-size samplers that operate at a few L/min as well as area samplers that operate at higher flow rates can be made based on the suggested design. Performance of such samplers can be predicted with high accuracy employing well-established impaction theory.

1. Introduction

Currently, a target specification for size-selective sampling instruments is determined by inhalable, thoracic, and respirable sampling conventions agreed upon internationally [1, 2, 3]. Various particle inertial classification devices are available to fractionate airborne particles to approximate one of the mentioned size-selective sampling criteria. The Button Sampler (SKC Inc., Eighty Four, PA), IOM Sampler (SKC Inc., Eighty Four, PA), GSP Sampler (Strohlein GmbH, Kaarst, Germany), and the Seven-Hole Sampler (Casella CEL Ltd., Bedford, UK) are examples of devices where the inhalable convention is followed well through the appropriate combination of inlet size, shape, and sampling flow rate [4, 5, 6]. Cyclones are the samplers most often used to separate thoracic or respirable fractions of inhalable particulates. A number of respirable and thoracic cyclones operating at flow rates ranging from 1.0 L/min to 10.0 L/min are available from different manufacturers. Extensive studies of different cyclonic samplers have shown, however, that the sampling characteristics of cyclones do not follow the entire ACGIH/CEN/ISO-defined respirable or thoracic sampling convention accurately [7, 8, 9, 10, 11, 12]. In most cases, cyclones oversample smaller particles and undersample larger ones as compared to the above mentioned conventions. Additionally, the performance of some personal respirable cyclones may be altered by particle build-up on the inner walls of the cyclone and particle re-entrainment and bounce-off [8, 13].

The use of porous polyurethane foam (PUF) as an alternative to cyclones has been proposed and is an inexpensive method for particle size-selective sampling [13, 14, 15, 16]. However, the particle separation using foams does not provide more accurate results when compared to those obtained using cyclones. Another alternative to traditional cyclones is a virtual cyclone – this device is based on a non-impact particle separation [17]. A respirable sampler employing the virtual cyclone concept was designed and shown to be able to closely follow the respirable convention [18].

In general, conventional inertial impactors, the most well known and studied inertial particle separators, cannot be used for thoracic or respirable particle collection due to the impactor's sharp cut-off characteristics. In 1978, Marple suggested the method to fractionate particles according to predetermined convention using a number of conventional impactors with different cut-offs [19]. A sampler proposed by Marple contained a number of inertial impactors arranged in parallel where each impactor simulated part of the predetermined curve so that overall performance of the sampler followed the entire selected curve. Different cut-offs were achieved using sets of differently sized nozzles. The aerosol was divided equally among different nozzle sets using an appropriate number of nozzles in each set. For example, to match the ACGIH respirable curve that was valid at that time, Marple used one 2.4-mm, eight 0.87-mm, and fifty-three 0.33-mm nozzles to provide 5.8, 3.5, and 2.2 μm 50% cut-offs at 2.0 L/min [19]. A similar approach can be used to design samplers for nearly any flow rate, with penetration characteristics that approximate any monotonically decreasing penetration curve [20]. Several single-stage two- and three-cut-off personal impactors with respirable aerosol penetration characteristics were designed and tested [21, 22]. Sampler prototypes with two cut-offs were found to work well, however, the smallest cut-off nozzles did not work properly in the three-cut-off sampler [22, 23].

Jones [23] suggested respirable and thoracic samplers that included a number of separate single-inlet impactors with different cut-offs arranged in parallel. In this design, each impactor had its own collection substrate and filter. In addition, each impactor had an independent flow control valve to maintain the appropriate flow rate through each impactor. Therefore, the sampler proposed by Jones was bulky and inconvenient to use [23]. Other researchers also used the approach of dividing a specific curve into increments: John [24] described a universal impactor for particle sampling within selected criteria and Chen et al. [14] used foams of different porosity placed in parallel to simulate the respirable curve.

As discussed above, several impactors arranged in parallel can be employed to build a sampler capable of simulating a predetermined curve accurately. However, none of the above mentioned samplers using the parallel impactor technique found its application in industrial hygiene. One reason for this, in the authors' opinion, was the lack of reliable and convenient design. This paper presents a novel sampler design [25] that contains a number of impactors arranged in parallel. During this study, several personal sampler prototypes were built, tested, and shown to be in good agreement with the sampling criteria for which they were designed.

2. Parallel particle impactor design

Performance of an inertial impactor is defined in terms of its 50% cut-off size, d_{50}. This means that 50% of cut-off-size particles penetrate through the impactor and the other 50% are collected on the impaction plate. The d_{50} can be found using the following equation [26, 27]:

$$d_{50} = \left(\frac{9 \mu W Stk_{50}}{\rho_p V_o C} \right)^{1/2}, \tag{1}$$

where μ is air viscosity, W is the width or diameter of the impactor nozzle, Stk_{50} is the Stokes number corresponding to a 50% particle cut-off, ρ_p is the particle density, V_0 is average air velocity in the nozzle, and C is the size-dependent Cunningham slip correction factor. The Stk_{50} depends on the Reynolds number of the flow, *Re*, jet-to-plate distance, *S*, and impactor nozzle throat length, *T*. The Stokes number may change significantly if porous material is used as a collection substrate [28, 29].

Typically, particle penetration through the conventional impactor decreases sharply from 100% to 0% near the 50% cut-off point. The solid line in Figure 1 represents a penetration curve for an impactor with a d_{50}=4.0 μm. The dashed curve in Figure 1 shows the respirable convention which has the same 50% cut-off of 4.0 μm as the single impactor. Despite the fact that both curves have a d_{50}=4.0 μm, it is clear that the conventional impactor (solid curve in Figure 1) will significantly oversample particles smaller than 4.0 μm and undersample particles larger than 4.0 μm compared to the respirable convention (dashed curve in Figure 1). As discussed, the curve of any predetermined shape may be approximated by combining several impactors in parallel [19, 21]. The square symbols in Figure 1 show the shape of a penetration curve of a hypothetical sampler containing two impactors arranged in parallel where one of the impactors has a 50% cut-off of 2.95 μm and the other has a d_{50} of 5.35 μm. The selected cut-off sizes correspond to 75% (midpoint of 50-100) and 25% (midpoint of 0-50) penetration efficiency of the respirable convention [19]. These numbers were determined based on the condition that the flow rate through each impactor is the same and equal to half of the total flow rate through the sampler. The curves in Figure 1 representing penetration through samplers containing four and six impactors (triangular symbols and circular symbols respectively) were constructed in a manner similar to that described above. The airflow through the individual impactors in these samplers is equal as it was in the sampler containing two impactors. The flow through a single impactor is one-fourth of the total flow for the sampler containing four impactors and one-sixth in the case of the six-impactor sampler. The curves presented in Figure 1 show that the respirable convention can be simulated rather closely using a sampler containing four or more impactors arranged in parallel.

The above described procedures can be applied to model a sampler with characteristics simulating the shape of any predetermined curve. The first step is to decide the number of impactors to be used and the overall flow rate through the sampler. The second step is to determine the cut-off sizes for each impactor according to the shape of the curve the sampler is to simulate and the flow rate through the individual impactor chosen. With this information, the inlet nozzle sizes of individual impactors can be defined easily using well-established impaction theory [27].

Control of the airflow through the individual impactors should be addressed when designing a sampler containing a number of impactors arranged in parallel. Marple's design was based on the assumption that the pressure drop across the impactor nozzle, Δ*P*, is approximately equal to the dynamic pressure of the air jet in the nozzle [19]:

$$\Delta P = \frac{1}{2} \rho V_0, \tag{2}$$

where ρ is air density and V_0 is the average air velocity in the nozzle. The amount of air for each cut-off was then controlled by the appropriate size and number of nozzles for each cut-off assuming that the air velocity in each nozzle of the sampler was approximately the same. Jones [23] simply placed valves beneath each impactor to control the amount of air passing though each impactor.

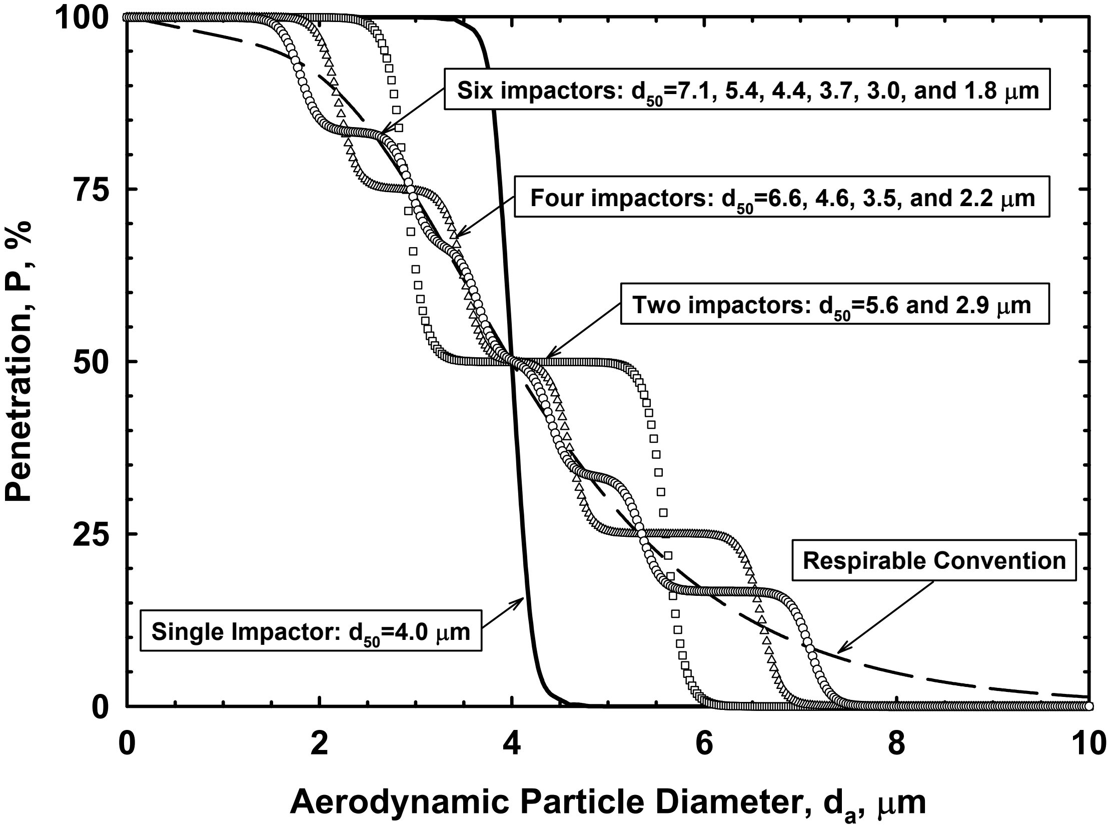

Figure 1. Comparison of the respirable convention curve with theoretically predicted performance of samplers containing a different number of inertial impactors arranged in parallel.

In the new sampler design, flow through each impactor is controlled using an appropriately sized exit orifice. Figure 2 shows schematically a sampler containing two impactors arranged in parallel. Both impactors are completely separated and each has an inlet nozzle, W_{In}, and exit orifice, W_{Out}. Since all inlets of the sampler are at the same atmospheric pressure and all outlets are connected to a single pump, the pressure drop across each impactor, ΔP_i, is the same and equal to the overall pressure drop across the whole sampler, ΔP_S:

$$\Delta P_S = \Delta P_1 = \Delta P_2. \tag{3}$$

Pressure drop across an individual impactor, ΔP_i, is a sum of pressure drops across the inlet nozzle, ΔP_{iIn}, and outlet orifice, ΔP_{iOut}:

$$\Delta P_i = \Delta P_{iIn} + \Delta P_{iOut}. \tag{4}$$

Using Equations 2, 3, and 4, the following equation may be written:

$$\frac{1}{2}\rho V_{1In}^2 + \frac{1}{2}\rho V_{1Out}^2 = \frac{1}{2}\rho V_{2In}^2 + \frac{1}{2}\rho V_{2Out}^2. \tag{5}$$

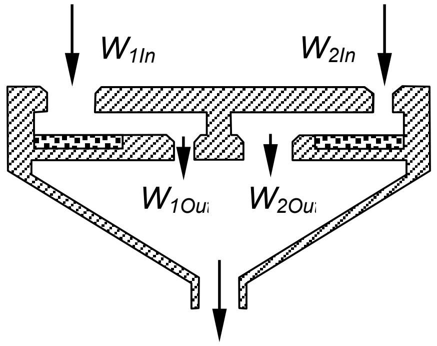

Figure 2. Schematic of sampler comprising two inertial impactors arranged in parallel.

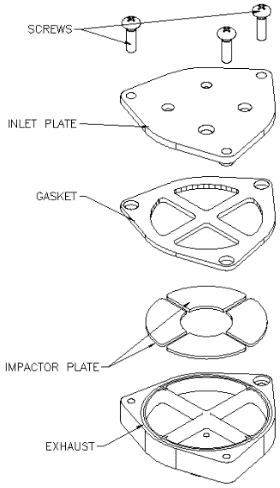

Figure 3. Schematic of prototype containing four impactors arranged in parallel impactor.

Equations 3, 4, and 5 can be extended for any number of impactors incorporated in the sampler. Thus, taking into account that airjet velocity in the nozzle $V=Q/(\pi(W/2)^2)$, Equation 5 for the sampler containing N impactors in parallel would be:

$$Q_1^2\left(\frac{1}{W_{1In}^4}+\frac{1}{W_{1Out}^4}\right)=Q_2^2\left(\frac{1}{W_{2In}^4}+\frac{1}{W_{2Out}^4}\right)=.....=Q_N^2\left(\frac{1}{W_{NIn}^4}+\frac{1}{W_{NOut}^4}\right). \tag{6}$$

As indicated earlier, the size of the inlet nozzle for each impactor is selected depending on the shape of the curve the sampler is going to simulate, the overall sampling flow rate, the desired particle size cut-offs, and the number of impactors in the sampler. The sizes of outlet orifices then can be calculated using Equation 6. Such a sampler can be designed for an overall flow that is equally distributed among all impactors ($Q_1=Q_2=\ldots=Q_N$) or a flow rate through each impactor may be set individually.

A schematic of a prototype sampler that includes four impactors arranged in parallel is shown in Figure 3. The prototype sampler has an inlet plate with impaction nozzles and an exhaust that is divided in four compartments. Each compartment includes collection substrate and an exit orifice. A gasket is used between the inlet plate and exhaust to prevent air leakage from outside and among individual impactors. Collection plates were cut out of a porous plastic support pad (Cat. No. 225-2902, SKC Inc., Eighty Four) and soaked with a few drops of silicone oil to minimize particle bounce and re-entrainment. Three prototype samplers were tested during this study: two respirable parallel particle impactors, RPPI2 and RPPI4, were designed to follow the respirable convention when operated at 2.0 and 4.0 L/min flow rates respectively. Thoracic parallel particle impactors (TPPI2) was designed to follow the thoracic curve when operated at 2.0 L/min. Parameters of these samplers are presented in Table 1. Nozzle sizes were calculated using value of Stokes number different from that suggested by impaction theory [27]. Lower value of Stokes number was based on other studies that show how porous collection substrate affects the performance of impactors [28, 29, 30] and our own experience using porous impaction substrate [31].

Table 1. Specifications of prototype samplers tested. Each sampler comprises four inertial impactors arranged in parallel.

Respirable Impactor, RPPI2 Q_S=2.0 L/min			Respirable Impactor, RPPI4 Q_S=4.0 L/min			Thoracic Impactor, TPPI2 Q_S=2.0 L/min		
D_{50}, μm	W_{In}, mm	W_{Out}, mm	D_{50}, μm	W_{In}, mm	W_{Out}, mm	D_{50}, μm	W_{In}, mm	W_{Out}, mm
6.5	3.45	1.68	6.5	2.59	1.30	17.5	5.10	2.15
4.6	2.71	1.72	4.6	2.06	1.33	11.9	4.00	2.18
3.5	2.26	1.80	3.5	1.73	1.40	8.9	3.25	2.25
2.3	1.68	3.45	2.3	1.30	2.59	4.8	2.15	5.10

3. Experimental methods

The performance of three parallel impactor prototypes was evaluated by measuring aerosol concentration upstream and downstream of the sampler using an Aerodynamic Particle Sizer (APS, Model 3320, TSI Inc., St. Paul, MN). A similar technique has been used widely by other researchers and is proven to allow accurate and rapid evaluation of particle samplers [13, 18, 22, 32, 33, 34]. Figure 4 shows a schematic of the experimental setup used in the study. The aerosol chamber was made of a clear plexiglass cylinder approximately four feet high and one foot in diameter. Test particles and HEPA-filtered dry air were introduced and mixed at the top of the chamber. Aerosol passed through a honeycomb flow straightener before reaching the test area where two identical sampling lines were installed. Air was expelled from the chamber through a 2.5-inch diameter hose to a biological safety cabinet (Model SG603, The Baker Company, Sanford, MN). The overall airflow through the chamber combining clean air and test aerosol ranged from 40 to 80 L/min resulting in a vertical air velocity in the chamber, V_{Ch}, from 10 to 20 mm/s. Thus, calm air conditions were simulated in the test chamber.

Three different aerosol generators were employed depending on the type of particle used. A six-jet Collison Nebulizer (BGI Inc., Waltham, MA) and a Sono Tek Ultrasonic Atomizer (Sono Tek Corporation, Milton, NY) were used to generate Potassium Sodium Tartrate (PST, Spectrum Chemical Mfg. Corp., Gardena, CA) and Dioctyl Phthalate (DOP, Spectrum Chemical Mfg. Corp., Gardena, CA). Glass spheres (GS, Spheriglass solid spheres, 10000E, Potters Industries Inc., Carlstandt, NJ) were aerosolized using a Fluidized Bed Aerosol Generator (Model 3400A, TSI Inc., St. Paul, MN). The charge on the generated particles was reduced to Boltzman equilibrium by passing test aerosol through five Polonium 210 Alpha source neutralizers (Model 2U500, NRD LLC, Grand Island, NY).

One of two identical sampling lines was used to measure aerosol size distribution in the chamber, $N_{Ch}(d_{ae})$. The second sampling line, on which the test sampler was mounted, was employed to register particle concentration downstream of the sampler, $N_{Down}(d_{ae})$. Ball valves were used to connect the required sampling line to the inlet of an Aerodynamic Particle Sizer (APS) placed beneath the chamber. In normal operating condition, the APS is sampling at 5.0 L/min. From this flow, 4.0 L/min is used as a sheath air and aerosol is sampled through the sensor at 1.0 L/min. In the setup, both sampling lines were connected directly to the 1.0 L/min aerosol sampling inlet using an air splitter which also enabled the addition or subtraction of makeup air so that flows through the sampler and the APS were maintained at required levels. The APS drew sheath air directly from the room.

During a single test, a set of six measurements lasting 60 seconds each was performed. $N_{Ch}(d_{ae})$ and $N_{Down}(d_{ae})$ were measured three times each alternating appropriate sampling lines to the APS inlet. Particle penetration $P(d_{ae})$ through the sampler was calculated using the following equation:

$$P(d_{ae}) = \frac{N_{Down}(d_{ae})}{N_{Ch}(d_{ae})} \times 100\% . \tag{7}$$

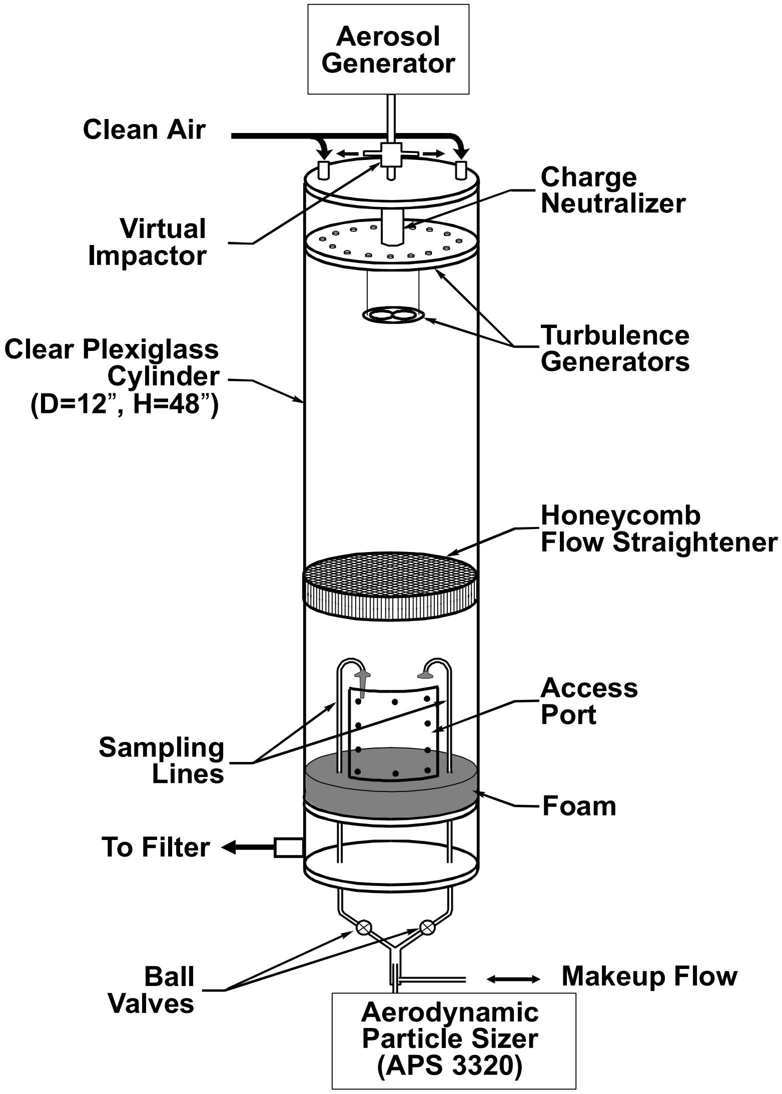

Figure 4. Schematic of experimental setup.

It is known that when using APS Model 3320 false large-particle counts may occur due to small particle recirculation in the optics chamber. To minimize this effect, overall particle concentration was kept below 80 cc^{-1}. A virtual impactor was employed, when needed, to minimize the number of particles smaller than 1.0 μm. APS calibration was checked periodically using NIST-traceable polymer microspheres of 1.0, 3.0, 4.0, 7.0, and 10.0 μm (Particle Counter Size Standards, Duke Scientific Corporation, Palo Alto, CA). The calibration of the APS was found to be stable and in good agreement with values provided by the manufacturer. In addition, the validity of the test technique was confirmed through testing several commercially available samplers. Data obtained for the respirable Higgins-Dewell Cyclone (Model BGI4CP, BGI, Inc., Walthman, MA) and thoracic cyclone (Model GK2.69, BGI, Inc., Walthman, MA) were in good agreement with previously reported results for similar samplers. Sampling characteristics measured for the Personal Environmental Monitor (PEM) (Model PEM 200-2-10, MSP Corporation, Shoreview, MN) also agreed well with manufacturer specifications.

4. Results and discussion

Individual impactors of the newly designed samplers were tested to confirm the theoretically predicted cut-off sizes. This was accomplished by closing three out of the four inlets so that air was pulled only through the inlet of the impactor to be tested. Single impactors were tested at a flow rate equal to one-fourth of the overall flow through the sampler because all sampler prototypes tested in this study were designed to have the overall sampling flow rate split equally among the individual inpactors of the sampler.

Data presented in Figure 5 show penetration as a function of particle aerodynamic size measured for each impactor composing prototype sampler RPPI2. PST test particles were used during these experiments. The symbols in the graph represent an average of at least three measurements and the error bars show standard deviation (the same applies for all other data presented in this paper). Solid lines represent the modeling of experimental data using the following sigmoid function:

$$P(d_{ae}) = \frac{a}{1+\exp\left\{-\frac{\left(d_{ae}-c\right)}{b}\right\}}. \tag{8}$$

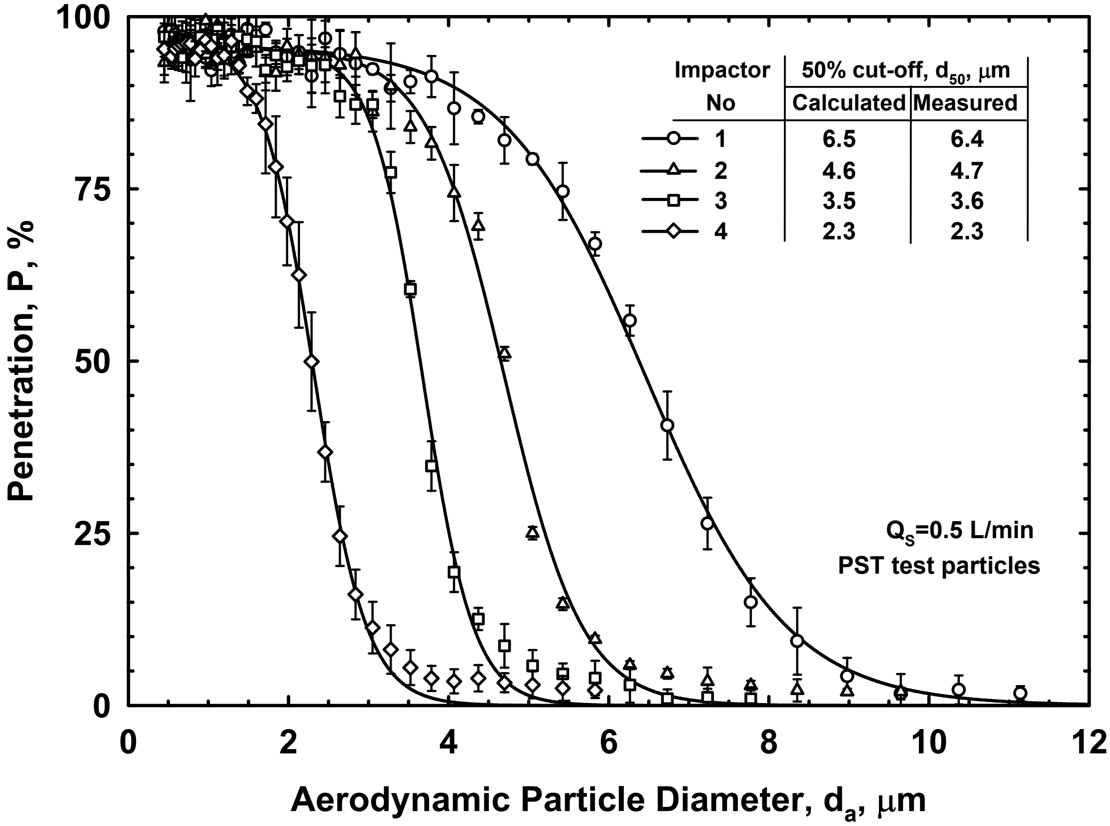

Figure 5. Particle penetration through individual impactors composing the RPPI2 respirable impactor.

The sigmoid function (Equation 8) was found to fit well with data obtained for the individual impactors tested. The same function was used by Kwon et al. [35] to fit collection efficiency data measured for a five-stage cascade impactor. Once constants *a*, *b*, and *c* were found for the best fit, Equation 8 was used to calculate d_{50}. The table in the corner of Figure 5 includes calculated and measured 50% cut-off sizes for each impactor incorporated in the RPPI2 sampler. The data shows that the measured d_{50} are in very good agreement with theoretically predicted values. Agreement was similarly good between the design and the experimental d_{50} for the impactors composing samplers RPPI4 and TPPI2.

Figure 6 shows the penetration characteristics of prototype sampler RPPI2. The open circles represent the initial performance of the sampler, i.e., the sampler was tested with new, clean collection substrates installed. The solid triangles show the penetration measured for sampler RPPI2 after it was exposed to coal mine dust for six hours. Figure 6 also includes a curve representing the respirable convention (solid line) and a curve mathematically constructed using data obtained for individual impactors (dashed line). The latter simulates the respirable curve more smoothly than was theoretically predicted for the sampler containing four impactors (Figure 1). The theoretical prediction was based on the assumption that all four impactors have sharp penetration characteristics as shown in Figure 1 for a single impactor. However, the data (Figure 5) indicate that the actual shape of the penetration curves for all individual impactors is not as steep as the one employed during mathematical simulation. Thus, the combined performance of the four impactors arranged in parallel is smoother (Figure 6, dashed line) when compared to the predicted characteristics (Figure 1, triangles). The initial overall penetration measured for the RPPI2 sampler (circles) follows closely the respirable curve (solid line) and the curve constructed using individual impactor data (dashed line). Thus, data presented in Figure 6 indicate that the performance of the RPPI2 sampler is in good agreement with the entire respirable convention, and, at the same time show the validity of the new design.

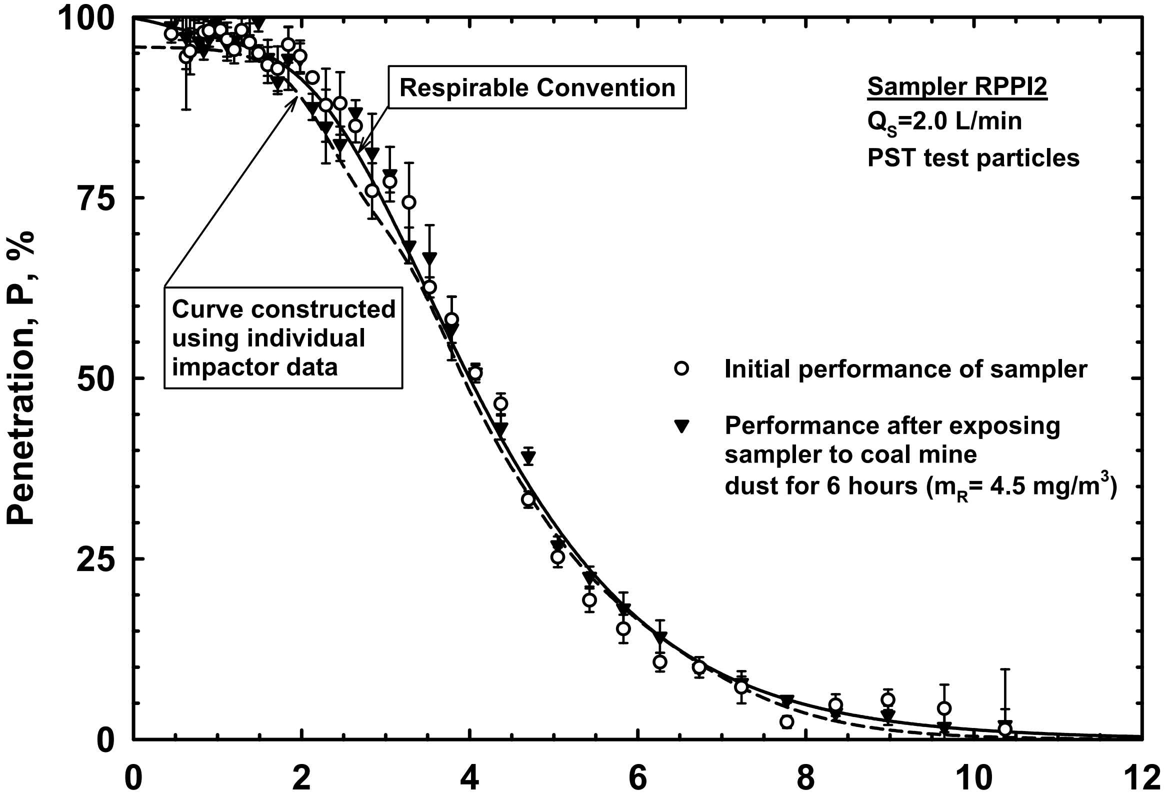

Figure 6. Comparison of performance of RPPI2 sampler with respirable convention.

To assess loading effect on the performance of the RPPI2 and RPPI4 samplers, they were operated for six hours in a Marple chamber at the NIOSH Pittsburgh Research Laboratory (Pittsburgh, PA). The mass of respirable fraction of Keystone coal dust measured using a Higgins-Dewell (HD) respirable cyclone was 4.76 mg/m^3. During an earlier study using the same Marple chamber under similar conditions [36], it was established that the size distribution of Keystone coal dust had mass median aerodynamic diameter (MMAD) equal to 3.91 μm and a geometric standard deviation (GSD) equal to 3.05. It can be shown that the mass of respirable fraction for the mentioned size distribution would make approximately 50 % of the total mass. Thus, we can conclude that the collection plates of RPPI2 and RPPI4 samplers were loaded with approximately 3.4 and 6.8 mg of coal dust respectively. As shown in Figure 6 (solid triangles), such load did not affect the performance of the RPPI2 sampler: neither particle bounce-off nor blow-off of collected particles was observed. The same was found to be valid for the RPPI4 sampler. These findings are in agreement with the stable performance of oil-impregnated porous impaction plates as reported by Marple and McCormack [18].

It is known that solid particles tend to be more bouncy than liquid particles. For this reason, sampler performance is often assessed using both types of test particles. Therefore, in addition to the potassium sodium tartrate (PST) particles recommended by ASTM standard D6061-01 [37], the parallel impactor samplers were also tested using glass microspheres (GS) and dioctyl phthalate (DOP) test particles. Figure 7 shows how three different types of test particles penetrate through the RPPI2 sampler. There is no significant difference in sampler performance obtained using PST, GS, or DOP test particles. In all cases, sampling characteristics stayed close to the respirable convention – the curve the sampler was designed to follow. Thus, it can be concluded that the sampler containing four impactors arranged in parallel collects liquid and solid particles similarly and that there is no indication of increased particle bounce even for smooth-surface, high-density glass spheres.

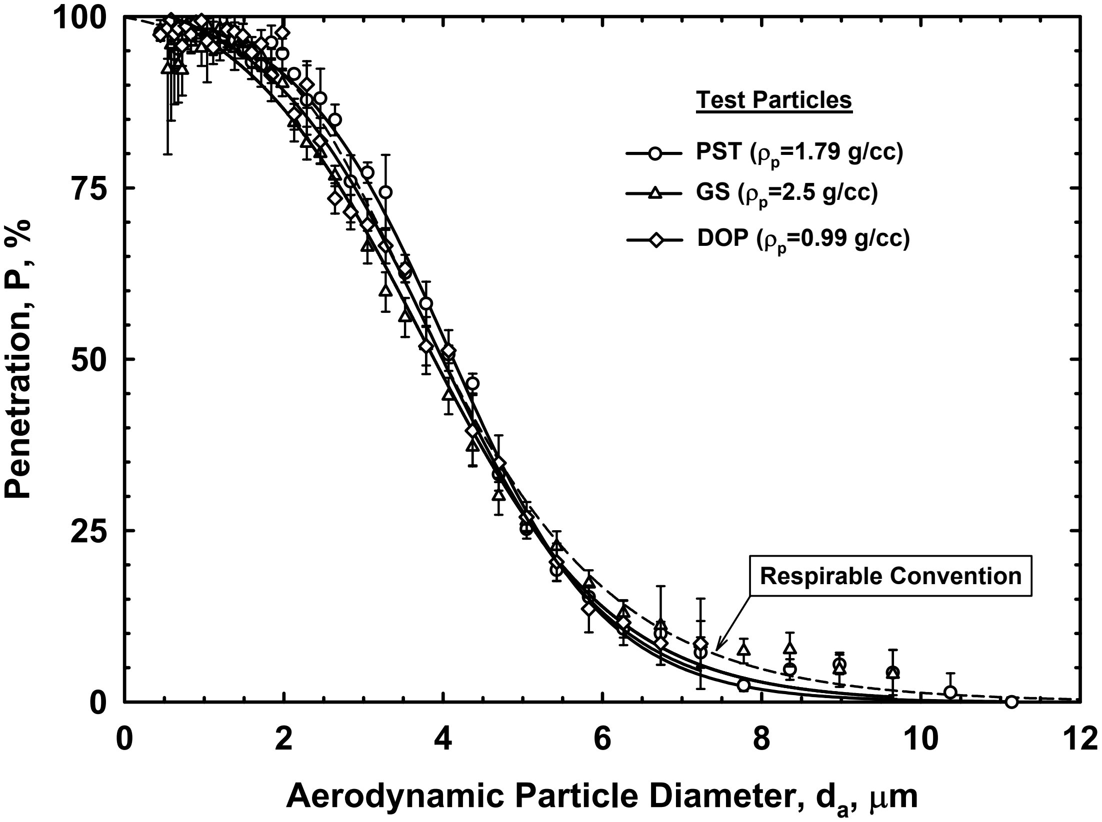

Figure 7. Comparison of penetration characteristics of the RPPI2 sampler obtained using different test particles.

Figure 8 compares the respirable convention with the penetration characteristics measured for the parallel impactor samplers and the Higgins-Dewell type respirable cyclone. All three samplers were tested using PST test aerosol and identical test procedures. The data for the HD Cyclone is in good agreement with results reported by Bartley et al. [7] and Maynard and Kenny [11] for a metal cyclone of a similar geometry. Although neither of these two studies tested the cyclone at a 2.2 L/min sampling flow rate, data presented in both studies suggest that at this particular flow the cyclone will match the respirable convention best. Nevertheless, the HD Cyclone oversamples smaller particles and undersamples larger ones (Figure 8., solid squares) when compared to the respirable convention as do many other cyclonic samplers [8, 9, 10, 12]. The results presented in Figure 8 clearly indicate that both newly designed parallel impactor samplers follow the respirable convention more closely than the respirable cyclone tested.

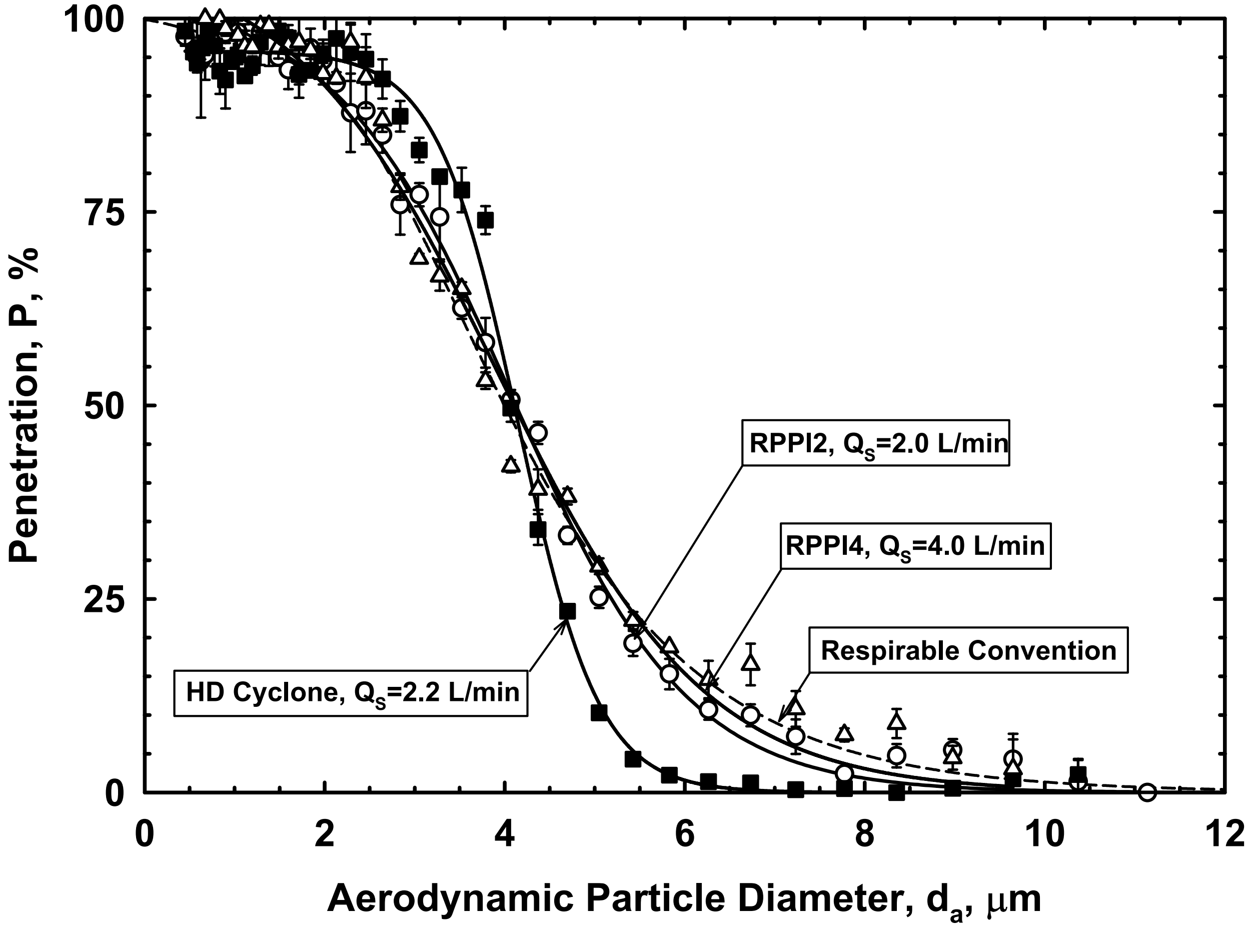

Figure 8. Comparison of penetration characteristics measured for the RPPI2 and RPPI4 parallel impactor samplers and HD Cyclone.

Comparison of the bias maps plotted for the RPPI4 sampler and the HD Cyclone (Figure 9) leads to a similar conclusion: the parallel impactor outperforms the cyclonic sampler. Bias mapping is a widely accepted way to present the performance of a sampler [7, 9, 37]. As discussed earlier, the mathematical model (Equation 8) was used to fit experimental data. Once the model for the sampler in question is established, it can be used to calculate the mass concentration sampled by this sampler, C_{Samp}, for any chosen aerosol size distribution. If C_R is the concentration measured by an ideal respirable sampler, then mean relative bias, Δ, is defined as follows [7, 37]:

$$\Delta = \frac{C_{Samp} - C_R}{C_{Samp}} \tag{9}$$

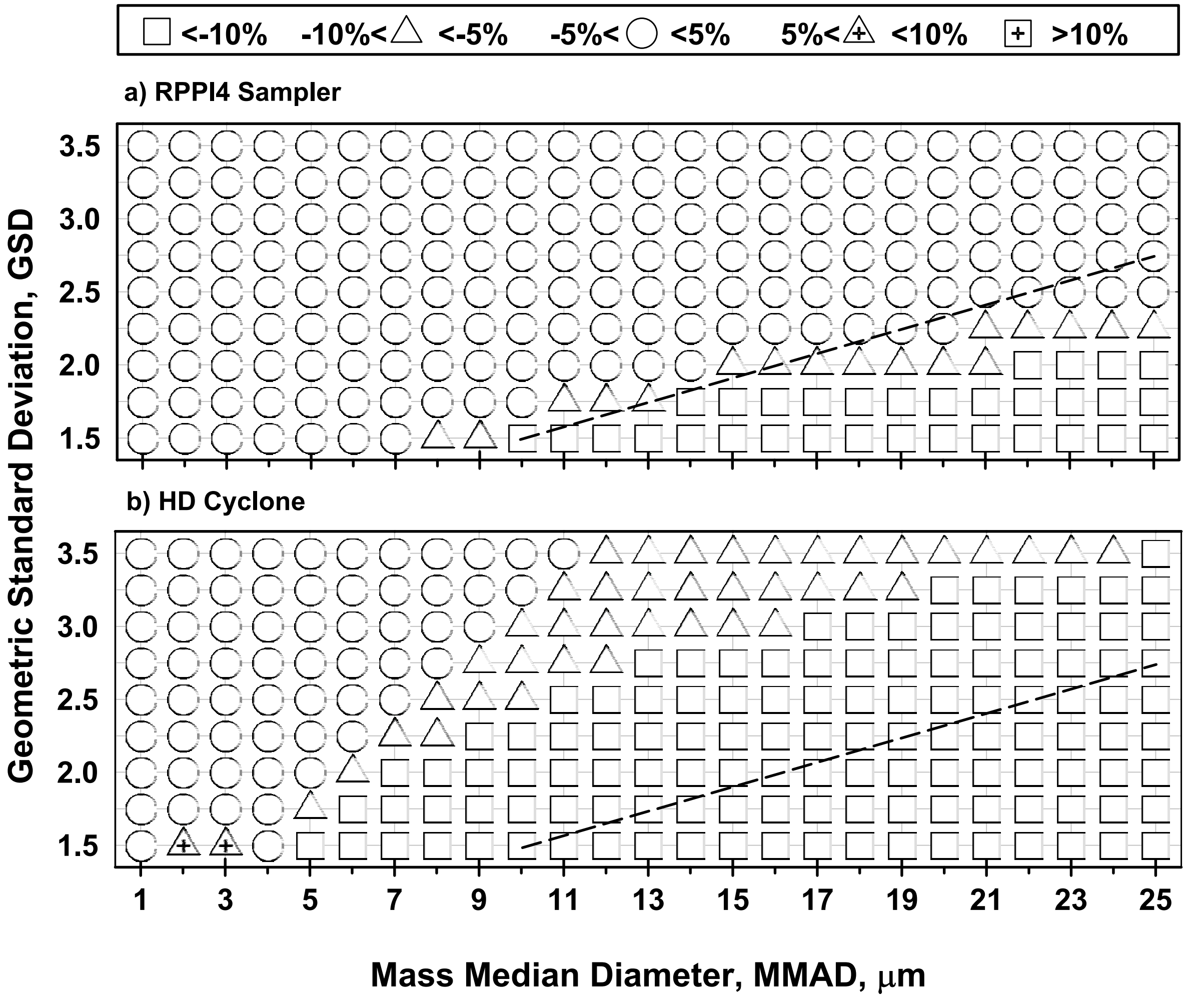

Figure 9. Bias maps plotted for the RPPI4 respirable sampler and the HD Cyclone.

Figure 9 includes the RPPI4 sampler and HD Cyclone bias charts for lognormal aerosol size distributions with geometric standard deviations between 1.5 and 3.5 and mass median diameters of < 25 μm. Data show that for a wide range of aerosol size distribution, particulate mass measured using the RPPI4 sampler will not differ by more than ± 5 % from the mass collected using an ideal respirable sampler. This difference falls below –10 % only for the rare narrow distribution of large aerosol (small GSD and large MMAD) which can be excluded from sampler evaluation. Per ASTM D60061-01 [37], the respirable sampler would only be evaluated at aerosol size distributions where the respirable fraction is greater than 5 % of a total aerosol. This omits sizes below the dashed line in Figures 9a and 9b defined by: (MMAD,GSD) = (10 μm, 1.5) to (25 μm, 2.75) [37]. Data provided in Figure 9 shows that the HD Cyclone will provide less accurate results compare to the RPI4 sampler.

Figure 10 includes penetration data for the newly designed thoracic parallel impactor sampler (TPPI2), Personal Environmental Monitor (PEM 10, MSP Corporation, Shoreview, MN), and GK2.69 Cyclone (BGI, Inc., Waltham, MA). Figure 10 also shows a curve representing the thoracic convention. As indicated earlier, the TPPI2 sampler was designed using the parallel impactor concept to meet the thoracic convention at a 2.0 L/min sampling flow rate. According to manufacturer specifications, the PEM 10 is designed to have a 10.0 μm 50% cut-off at a sampling flow rate of 2.0 L/min and the GK2.69 Cyclone will conform to the thoracic curve at 1.6 L/min.

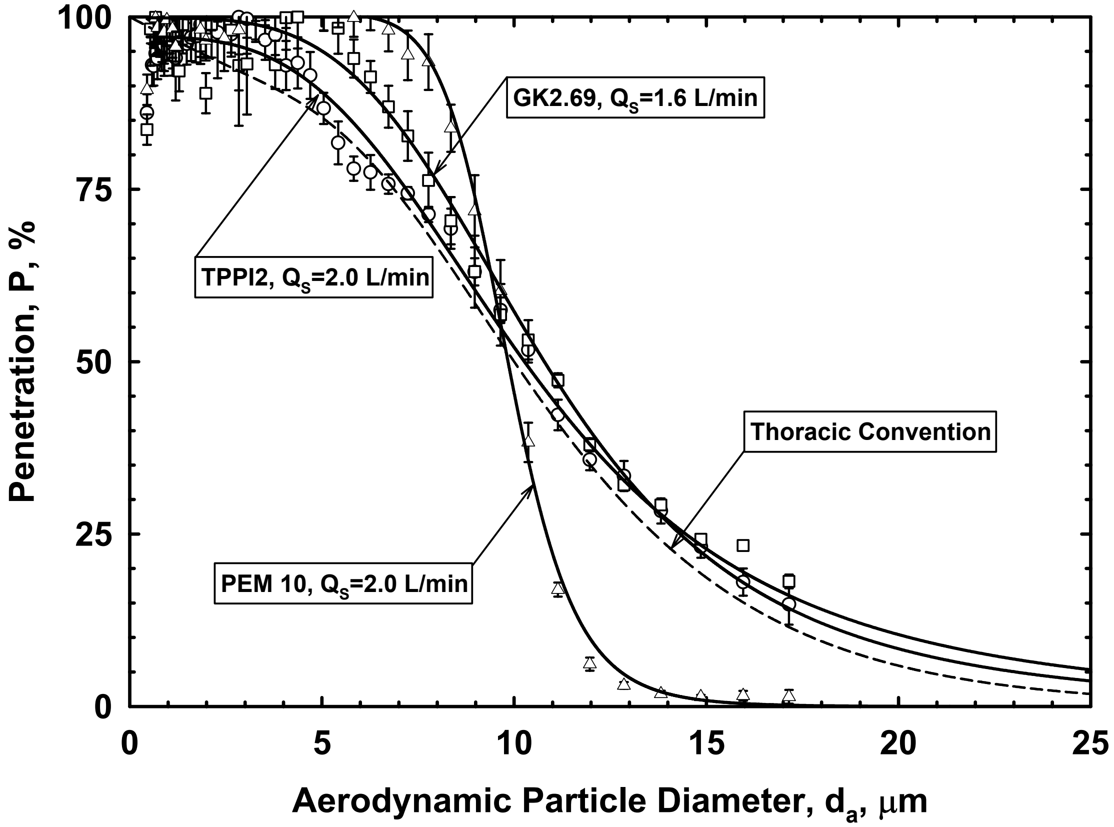

Figure 10. Comparison of penetration measured for TPPI2 sampler, GK2.69 cyclone, and PEM 10.

Penetration of PST test particles measured for the TPPI2 sampler (Figure 10, circles) demonstrates good agreement with the thoracic convention. It should be noted that the tests did not include a thorough evaluation of inlet aspiration efficiency which may influence results for particles larger than 10 µm. Also, reliable data was not produced for particles larger than approximately 17 µm due to the low particle count above that size. Experimental data were fitted and performance of the TPPI2 sampler was extrapolated for larger particle sizes using the following model:

$$P(d_{ae}) = \frac{a}{1+\left(\frac{d_{ae}}{b}\right)^{c}}. \tag{10}$$

The same equation was used to model penetration data obtained for the GK2.69 Cyclone (squares in Figure 10).

Experimental data for the PEM 10 (triangles in Figure 10) show good agreement with manufacturer specifications. Penetration characteristics measured for the GK2.69 Cyclone (squares in Figure 10) conform well with sampler specifications and with results reported by Maynard [33]. These facts indicate that the test system used in this study provides accurate results in the larger particle range despite the limitations mentioned earlier. Thus, it can be concluded that the newly designed TPPI2 sampler closely follows the entire thoracic convention.

5. Conclusion

The novel design of a sampler comprising a number of inertial impactors arranged in parallel was applied to manufacture two respirable samplers operating at a 2.0 and 4.0 L/min sampling flow rate and one sampler approximating the thoracic convention at 2.0 L/min. Each sampler incorporated four impactors arranged in parallel. Test results for all samplers showed good agreement with predicted characteristics. Penetration characteristics of both respirable samplers followed the entire respirable convention more closely when compared to the performance of the commercially available and widely used Higgins-Dewell respirable cyclone. The newly designed thoracic sampler also performed as predicted and showed good agreement with the entire thoracic convention.

Using solid and liquid test particles, it was shown during this study that performance of the newly designed samplers does not depend on the type of particles collected. Experiments revealed also that an approximate load of 6.4 mg of coal mine dust on the sampler collection plates did not affect the performance of the new sampler.

The suggested parallel impactor arrangement can be used to design samplers that will accurately fractionate inhalable particles according to predetermined characteristics including the ACGIH/CEN/ISO-defined respirable and thoracic conventions or any other monotonically decreasing penetration curve. The new design can be applied to fabricate personal samplers operating at a few liters per minute or area samplers operating at higher flow rates. Parameters of samplers with parallel impactors can be predicted with high accuracy. The suggested parallel impactor design insures consistent sampler performance for different types of aerosol and a wide range of particle concentrations.

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References

[1] ISO 1995 ISO 7708:1995(E) Air Quality – Particle Size Fraction Definitions for Health-related Sampling (Geneve: ISO)

[2] CEN 1993 CEN Standard EN 481, Workplace Atmospheres: Size Fraction Definitions for Measurement of Airborne Particles in the Workplace (Brussels: CEN)

[3] ACGIH 2003 TLVs® and BEIs® (Cincinnati:ACGIH)

[4] Aizenberg V, Grinshpun S A, Willeke K, Smith J and Baron P A 2000 Measurement of the Sampling Efficiency of Personal Inhalable Aerosol Samplers Using a Simplified Protocol J. Aerosol Sci. **31** 169-179

[5] Kenny L C, Aitken R, Chalmers C, Fabries J F, Gonzales-Fernandez E, Kromhout H, Liden G, Mark D, Riediger G and Prodi V 1997 A Collaborative European Study of Personal Inhalable Aerosol Sampler Performance Ann. occup. Hyg **41** 135-153

[6] Kenny L C, Aitken R, Baldwin P E J, Beaumont G C and Maynard A D 1999 The Sampling Efficiency of Personal Inhalable Aerosol Sampler in Low Air Movement Environments J. Aerosol Sci. **30** 627-638

[7] Bartley D L, Chen C C, Song R and Fischbach T J 1994 Respirable Aerosol Sampler Performance Testing Am. Ind. Hyg. Assoc. J. **55** 1036-1046

[8] Chen C C and Huang S H 1999 Shift of Aerosol Penetration in Respirable Cyclone Samplers Am. Ind. Hyg. Assoc. J. **60** 720-729

[9] Gorner P, Wrobel R, Micka V, Skoda V, Denis J and Fabries J F 2001 Study of Fifteen Respirable Aerosol Samplers Used in Occupational Hygiene Ann. Occup. Hyg. **45** 43-54

[10] Liden G and Kenny L C 1993 Optimization of the Performance of Existing Respirable Dust Samplers Appl. Occup. Environ. Hyg. **8** 386-391

[11] Maynard A D and Kenny L C 1995 Performance Assessment of Three Personal Cyclone Models, Using an Aerodynamic Particle Sizer J. Aerosol Sci. **26** 671-684

[12] Trakumas S and Hall P 2003 Performance Assessment of Personal Respirable Cyclone

Samplers Abstracts American Industrial Hygiene Conference & Exposition (Dallas) p 45

[13] Chen C C, Lai C Y, Shih T S and Hwang J S 1999 Laboratory Performance Comparison of Respirable Samplers Am. Ind. Hyg. Assoc. J. **60** 601-611

[14] Chen C C, Lai C Y, Shih T S and Yeh W Y 1998 Development of Respirable Aerosol Samplers Using Porous Foams Am. Ind. Hyg. Assoc. J. **59** 766-773

[15] Gorner P, Wrobel R, Mohlmann C, Aitken R J, Kenny L C and Fabries J F 2002 Performances of European Multifractional Aerosol Samplers Abstracts 21th Annual AAAR Conference (Charlotte) p 35

[16] Kenny L, Chung K, Dilworth M, Hammond C, Wyn Jones J, Shreeve Z and Winton J 2001 Applications of Low-cost, Dual-fraction Dust Samplers Ann. occup. Hyg. **45** 34-42

[17] Torczynski J R and Rader D J 1997 The Virtual Cyclone: A Device for Nonimpact Particle Separation Aerosol Sci. Techno. **26** 560-573

[18] Chen C C, Huang S H, Lin W Y, Shih T S and Jeng F T 1999 The Virtual Cyclone as a Personal Respirable Sampler Aerosol Sci. Techno. **31** 422-432

[19] Marple V A 1978 Simulation of Respirable Penetration Characteristics by Inertial Impaction J. Aerosol Sci. **9** 125-134

[20] Marple V A, Rubow K L and Olson B.A 1993 Inertial, Gravitational, Centrifugal, and Thermal Collection Techniques Aerosol Measurement: Principles, Techniques, and Applications ed K Willeke and P A Baron (New York: Van Nostrand Reinhold) pp 206-232

[21] Marple V A and McCormack J E 1983 Personal Sampling Impactor with Respirable Aerosol Penetration Characteristics Am. Ind. Hyg. Assoc. J. **44** 916-922

[22] Baron P A 1983 Sampler Evaluation with an Aerodynamic Particle Sizer Aerosols in the Mining and Industrial Work Environment ed V A Marple and B Y H Liu (Ann Arbor: Ann Arbor Science) pp 861-877

[23] Jones G W 1987 Design and Calibration of a Multi-Purpose Aerosol Sampler Doctoral dissertation. Graduate School of Public Health (Pittsburgh: University of Pittsburgh)

[24] John W 1994 Universal Impactor for Particle Collection within Sampling Criteria Abstracts 13th Annual AAAR Conference (Los Angeles) p 929

[25] U.S. Patent 7,073,402

[26] Marple V A and Willeke K 1976 Impactor Design Atmos. Envir. **10** 891-896

[27] Rader D J and Marple V A 1985 Effect of Ultra-Stokesian Drag and Particle Interception on Impaction Characteristics Aerosol Sci. Techno. **4** 141-156

[28] Kavouras I G and Koutrakis P 2001 Use of Polyurethane Foam as the Impaction Substrate/Collection Medium in Conventional Inertial Impactors Aerosol Sci. Techno **34** 46-56

[29] Marjamaki M and Keskinen J 2004 Effect of Impaction Plate Roughness and Porosity on Collection Efficiency J. Aerosol Sci. **35** 301-308

[30] Demokritou P, Gupta T, Ferguson S and Koutrakis P 2002 Development and Laboratory Performance Evaluation of a Personal Cascade Impactor J. Air & Waste Manage. Assoc. **52** 1230-1237

[31] Trakumas S and Hall P 2002 Modification and Validation of Diesel Particulate Matter Cassette for PM-1.0 Sampling at Different Flow Rates Abstracts 2002 American Industrial Hygiene Conference & Exposition (San Diego) p 19

[32] Maynard A D, Kenny L C and Baldwin E J 1999 Development of a System to Rapidly Measure Sampler Penetration up to 20 μm Aerodynamic Diameter in Calm Air, Using the Aerodynamic Particle Sizer J. Aerosol Sci. **30** 1215-1226

[33] Maynard A D 1999 Measurement of Aerosol Penetration Through Six Personal Thoracic Samplers Under Calm Air Conditions J. Aerosol Sci. **30** 1227-1252

[34] Trunov M, Trakumas S, Willeke K, Grinshpun S A and Reponen T 2001 Collection of Bioaerosol Particles by Impaction: Effect of Fungal Spore Agglomeration and Bounce Aerosol Sci. Techno. **35** 617-624

[35] Kwon S B, Lim K S, Jung J S, Bae G N and Lee K W 2003 Design and Calibration of a 5-stage

Cascade Impactor (K-JIST Cascade Impactor) J. Aerosol Sci. **34** 289-300

[36] Volkwein J C, Tuchman D P and Vinson R P 2002 Performance of a Prototype Personal Dust Monitor for Coal Mine Use Mine Ventilation ed E De Souza (Lisse: A.A.Balkema Publishers) pp 633-639.

[37] ASTM 2003 D6061-01: Standard Practice for Evaluating the Performance of Respirable Aerosol Samplers Annual Book of ASTM Standards (West Conshohocken: ASTM)