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Laboratory comparison of new high flow rate respirable size-selective sampler

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Abstract

A newly developed high flow rate respirable size-selective cyclone sampler (GK4.162—also known as the Respirable Air Sampling Cyclone Aluminum Large (RASCAL)) was calibrated to determine its optimum operating flow rate. The Health and Safety Laboratory in the United Kingdom and two laboratories from the National Institute for Occupational Safety and Health in the United States conducted experiments using two different methods: (1) polydisperse aerosol and time-of-flight direct reading instrument (Aerodynamic Particle Sizer (APS)) and (2) monodisperse aerosol and APS. The measured performance data for the cyclone was assessed against the international respirable convention using the bias map approach. Although the GK4.162 cyclone was tested using different aerosols and detection methods, the results from the three laboratories were generally similar. The recommended flow rate based on the agreement of results from the laboratories was 9.0L/min.

Keywords

Cut point (d_{50}); GK4.162; high flow rate; respirable size-selective sampler; sampler bias; sampling efficiency

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The findings and conclusions in this article are those of the authors and do not necessarily represent the official position of the National Institute for Occupational Safety and Health (NIOSH), Centers for Disease Control and Prevention (CDC), or the Health and Safety Executive (UK). Mention of company names or products does not constitute endorsement by the NIOSH.

Introduction

Recently, the Occupational Safety and Health Administration (OSHA) issued new standards for respirable crystalline silica (RCS) to better protect workers from exposure. OSHA is already enforcing these standards for the construction industry, and will apply them to the general and maritime industries on June 23, 2018.[1] The new standards include the statement that “the employer shall ensure that no employee is exposed to an airborne concentration of RCS in excess of 50 μg/m^3, calculated as an 8-hr time-weighted average (TWA) exposure and employee exposure will remain below 25 μg/m^3 as an 8-hr TWA under any foreseeable conditions.” The performances of respirable size-selective samplers operating at a higher flow rate (>4L/min) than traditional samplers (1.7 or 2.2 L/min flow rate) have been evaluated.[2–6] These are designed to collect more respirable dust for more accurate exposure assessment due to an unacceptable level of variation in low loading RCS samples and are included in the revised National Institute for Occupational Safety and Health (NIOSH) Manual of Analytical Methods for quartz measurement[7,8] as well as the Methods for the Determination of Hazardous Substances guidance document 101/2 (Health and Safety Executive).[9]

Another benefit of the high flow rate respirable size-selective samplers is in assessing the effectiveness of engineering dust controls for tools used during short-term tasks. When operated for a short duration for a task-based evaluation, low flow rate samplers (e.g., the Dorr-Oliver 10-mm nylon cyclone operating at 1.7L/min) may not achieve sample mass that is adequate to detect concentrations below the occupational exposure limits for RCS. For example, the lowest RCS exposures with dust controls for tools used to cut block and brick were reported as <0.05 mg/m^3 (lower than limit of detection) in 25-min samples.[10] Additionally, a study of saws used to cut concrete reported RCS concentrations with dust controls that ranged from <0.2 to <0.6 mg/m^3 in 15-min samples.[11] Therefore, quantifying RCS exposure at concentrations less than either the NIOSH-recommended exposure limit or OSHA’s new PEL of 0.05 mg/m^3 in short-term samples requires a higher flow rate sampler in order to collect a detectable amount of RCS.

BGI Inc. (currently Mesa Laboratories, Inc.) was tasked with designing and fabricating a respirable size-selective sampler based on the scalable model devised by Kenny and Gussman[12] (a natural extension of the GK2.69 cyclone). The diameter of the new cyclone (a manufacturing uncertainty of 0.0005 cm in 4.162 cm) is calculated from the Kenny-Gussman model for a cut-size of 4.0 mm at a flow rate of 10.0 L/min. The objective of this study was to compare performances of the newly developed GK4.162 high flow rate respirable size-selective sampler (Figure 1) in three different laboratories—the Health and Safety Laboratory (HSE’s laboratory, Great Britain) and two NIOSH laboratories (USA)—with each lab using its own preferred test methods and GK4.162 cyclone(s).

Methods

Sampling efficiency test

HSL — Sampling efficiency test with polydisperse aerosol—The evaluation method was consistent with that described in BS EN 13205, Workplace atmospheres—

Assessment of performance of instruments for measurement of airborne particle concentrations.[13–15] The design of the test system was based on that described by Kenny and Lidén[16] used for the measurement of aerosol penetration through the GK4.162 cyclone. The approach required measurements of the particle size distribution of an aerosol penetrating through the GK 4.162 cyclone and that of the aerosol challenging it. The two particle size distributions were compared to obtain its size-selective sampling performance.

A polydisperse aerosol of glass ballotini, 2.5 g/m^3 density, (Spheriglass 5000, mean diameter between 7 and 10 μm, Potters Industries Inc., South Yorkshire, UK) was generated in a calm air chamber using a rotating brush generator (Model RBG 1000, Palas GmbH, Karlsruhe, Germany). The charge level on the aerosol was reduced using an ionizing air blower (Model 961E, 3M, St. Paul, MN), to help the aerosol be stable both with time and position within the chamber.

A sampling tube was used to connect the cyclone located in the chamber to an aerodynamic particle sizer (APS 3321, TSI Inc., Shoreview, MN) located below the chamber. Both reference and cyclone connecting tubes were identical (inlet diameter 14.5 mm). The sampling tube to the cyclone was placed close to the exit of the vortex finder to minimize losses within the sampler. The dust generator was adjusted to give a concentration of particles that resulted in good penetration results, but which was not so high as to create particle counting errors within the APS instrument.

The APS operates at a flow rate of 5 L/min, which comprises 1 L/min through the accelerating inlet nozzle into the sensing volume and 4 L/min that is removed from the inlet flow, passed through a HEPA filter, and recombined with the sample flow at the acceleration nozzle as an annular sheath flow around the sample flow. In order to test at the required cyclone flow rates, the sheath flow was disconnected from the inlet and sampled from the surrounding lab air. The remaining air was introduced into the inlet as “make-up” air using an SKC Legacy pump (SKC Inc., Eighty-Four, PA), with a pulsation damping vessel, to give the required cyclone flow rate. The APS calibration was checked each day prior to testing using certified monodisperse latex spheres (Duke Scientific Corp., Fremont, CA).

The cyclone was characterized over a range of flow rates from 7–10 L/min using the following method. Samples of 1-min duration were drawn through each system in turn, allowing a sufficient time interval between samples to ensure complete replacement of aerosol in the tubing. In each case, three reference and two cyclone samples were taken alternatively between reference (R) and cyclone (C) (i.e., R-C-R-C-R), and three repeat measurements were made at each flow rate.

Reference and cyclone sampler particle concentrations were averaged at each particle size, and cyclone penetration was measured as a fraction of the reference aerosol. This data was transferred to a curve-fitting computer program (TableCurve, Systat Software Inc.), where the calculated fractional penetration was normalized to 1 at 1 μm to eliminate effects caused by nonlinearity of the APS inlet below this size. The particle size at which 50% of the particles penetrated the cyclone, known as the cut point (d_{50}), was then determined from the fitted curves.

NIOSH Laboratory #1—Sampling efficiency test with polydisperse aerosol— Solid soda-lime glass microspheres (2.5 g/m^3 density, Cospheric, Santa Barbara, CA) were generated in a calm air chamber[17] using a fluidized bed dust generator (Model 3400, TSI Inc.) and a Kr-85 aerosol neutralizer (Model 3054A, TSI Inc.). An APS (Model 3321, TSI Inc.) was used to measure the particle size distribution and its calibration was verified prior to the experiment with polystyrene latex (PSL) spheres (Thermo Fisher Scientific, Pittsburgh, PA). Two different sizes of soda-lime particles (mass median aerodynamic diameter (MMAD) 2 and 6 µm) were used for separate experiments. The mass concentration from each particle size was averaged to determine sampling efficiency of the GK4.162 cyclone.

The cyclone was placed horizontally in the chamber on the end of a stainless steel 3/8-in tube, which had a 180° bend just after the cyclone. The tube was then connected vertically to the APS located outside the chamber. An identical tube (3/8 in) without cyclone attached (reference sampling) was also positioned in the chamber to measure particles that entered the cyclone. Due to the fixed flow rate (5L/min) of the APS, additional air (make-up air) was extracted by using a mass-flow controller (Sierra, Monterey, CA) connected to a house vacuum to obtain the desired cyclone flow rates. The GK4.162 was tested at flow rates of 8, 8.5, 9.0, 9.5, and 10L/min, and the flow rate was verified by using a TetraCal calibrator (Mesa Labs Inc., Lakewood, CO). A system of valves (ASCO, Florham Park, NJ) was used to alternate the sampling tube connected to the APS. Five alternate sets of samples (three reference and two cyclone samples, i.e., R-C-R-C-R) were obtained for each dust and each flow rate. From the five sets, two penetration curves were generated and two characteristic d_{50} were determined for each flow rate.

NIOSH Laboratory #2—Sampling efficiency test with monodisperse aerosol— The sampling efficiency test for the GK4.162 cyclone was conducted in the calm air chamber that was used in previous studies.[2,18,19] The top plate of the chamber was modified to allow a Kr-85 aerosol neutralizer (Model 3054A, TSI Inc.) to be used in the drying column. At least seven different sizes of monodisperse ammonium fluorescein aerosols were generated using a vibrating orifice aerosol generator (VOAG, Model 3450, TSI Inc.) at a range of testing flow rates.[2,19,20] Aerodynamic particle size, particle concentration, and geometric standard deviation (GSD <1.1) were measured with an APS (Model 3321, TSI Inc.). The geometric mean of each particle size distribution measured by the APS was used as the aerodynamic diameter. The inlet of the GK4.162 cyclone was facing vertically and the reference sampler (25-mm open cowl sampler, SKC Inc.) were placed horizontally inside the chamber at the same sampling plane. The GK4.162 cyclone and reference samplers were loaded with 47- and 25-mm PVC filters, respectively (5-µm pore size, SKC Inc.). A 47-mm polypropylene conductive filter cassette (SKC Inc.) was used for the GK4.162 cyclone to minimize wall deposits.[21] The GK4.162 cyclone and reference samplers were tested at three different flow rates (8.5, 9, and 9.5L/min). The inlet diameter for the reference sampler was calculated in accordance with criteria for calm air sampling[22,23] to ensure minimum sampling bias (~100% aspiration efficiency). In order to minimize sampling efficiency error introduced from sampling pump pulsation,[24] sampling flow rates were controlled by mass flow controllers (model CFC 17, Aalborg, Orangeburg, NY), and sampling was conducted between 3 and 6 min depending on the generated particle size. Five repeat measurements with five different GK4.162 cyclones were conducted at each particle size and flow rate.

After sampling, the collection media were placed in 5% ammonium hydroxide solution to extract the fluorescein, and the fluorescent intensities of the extracted fluorescein solutions were measured using a luminescence spectrometer (LS50B, Perkins-Elmer, Waltham, MA).

Sampling efficiency comparison to the respirable convention—The measured sampling efficiencies for the GK4.162 cyclone was compared to the American Conference of Governmental Industrial Hygienists (ACGIH®)[25]/Comité Européen de Normalisation (CEN)[26]/International Standards Organization (ISO)[27]/respirable convention curve by calculating the bias. The estimated biases for each laboratory data were calculated using the bias map approach described in BS EN 13205[13] and previous studies.[14,15] The lognormal distribution was assumed, and the calculation ranges of MMAD and GSD were 1–25 µm and 1.5–3.5, respectively.

Results

HSL

The concentration of glass ballotini was stable inside the test chamber with minimal temporal fluctuation. The cyclone flow rate was checked before and after each test and was within 1% of the target value. All of these factors contributed to producing measurements that were repeatable. The resultant sampling efficiency curves for the GK4.162 cyclone along with the ACGIH[25]/CEN[26]/ISO[27] respirable convention are shown in Figure 2. Bias maps of the GK4.162 cyclone were generated from the measured sampling efficiency compared to the ACGIH[25]/CEN[26]/ISO[27] respirable convention and are shown in Figure 3. Negative and positive bias indicates an underestimation and overestimation of mass concentration by the GK4.162 cyclone compared to the respirable convention curve, respectively. The unshaded area in the bias maps indicates the range of MMAD and GSD values including the particle size distributions of most interest for workplace aerosol sampling.[13] The GK4.162 cyclone showed an overestimation up to 30% at a flow rate of 7.0 L/min, and showed an underestimation up to 20% at a flow rate of 10 L/min. Based on findings of the measured d_{50} and calculated bias between tested flow rates, a flow rate of 9.0 L/min resulted in minimal bias (ranged from −5% to 5%).

Measured d_{50} as a function of GK4.162 cyclone flow rate is shown in Figure 4 together with an empirical model of GK family cyclone.[12] The d_{50} of the model was calculated using the following equation:

$$\ln(d_{50}) = a + b\ln(d_C) - c\ln(\mathrm{Q}), \quad (1)$$

where d_{50} is the cut off diameter, d_C is the inside diameter of the cyclone body (cm), Q is the flow rate in liters per min, a = 0.962, b = 2.143, and c = 1.143 (empirical constants were determined using non-linear least-squares regression).

NIOSH Laboratory #1

The sampling efficiency curves for the GK4.162 cyclone tested with polydisperse soda lime particles along with the ACGIH[25]/CEN[26]/ISO[27] respirable convention are shown in Figure 5. Bias maps of the GK4.162 cyclone were generated from the measured sampling efficiency compared to the ACGIH[25]/CEN[26]/ISO[27] respirable convention and are shown in Figure 6. The GK4.162 cyclone showed an overestimation up to 18% at a flow rate of 8.0 L/min, and showed an underestimation up to 25% at a flow rate of 10 L/min. Based on findings of the d_{50} and calculated bias between tested flow rates, a flow rate of 9.0 L/min (ranged from −10% to 6%) or 9.5 L/min (ranged from 4 to −20%) resulted in minimal bias. Measured d_{50} as a function of GK4.162 cyclone flow rate is shown in Figure 4.

NIOSH Laboratory #2

The sampling efficiency curves for the GK4.162 cyclone tested with monodisperse ammonium fluorescein particles along with the ACGIH[25]/CEN[26]/ISO[27] respirable convention are shown in Figure 7. Each data point and error bar represent the average and standard deviation, respectively, of five GK4.162 cyclones. Bias maps of the GK4.162 cyclone were generated from the measured sampling efficiency compared to the ACGIH[25]/CEN[26]/ISO[27] respirable convention and are shown in Figure 8. The calculated bias at the flow rates of 8.5, 9, and 9.5 L/min ranged from 12 to −2%, 6 to −6%, and 2 to −26%, respectively. Based on findings of the d_{50} and calculated bias at different flow rates, a flow rate of 9.0 L/min resulted in minimal bias. Measured d_{50} as a function of GK4.162 cyclone flow rate is shown in Figure 4.

Discussion

The GK4.162 cyclone was developed as a member of the Gussman-Kenny (GK) family of cyclones,[12] which can be used as dual use samplers for respirable and thoracic size-selective sampling when operated at different flow rates. The recommended flow rate of the GK4.162 for thoracic size-selective sampling has been reported by three different laboratories.[19,28]

About two decades ago, the Aerosol Sampler Testing Exchange (ASTEX) study was conducted to compare the separation efficiency of the GK2.69 cyclone from eight different laboratories (a joint European/International Standard Committee—CEN/TC137/WG4 and ISO/TC146/SC2/WG1) to improve experimental methods and quality.[29,30] The study reported that the sampling efficiency curves of the GK2.69 were broadly similar with respect to d_{50} but some laboratories showed large variation for larger particle sizes.

The present study is similar to the ASTEX study but was carried out with a higher flow rate version of the GK2.69 cyclone. The results from the three laboratories were generally similar even though they used different test aerosols and detection methods. Measured d_{50} as a function of GK4.162 cyclone flow rate from the three different laboratories were close to each other (Figure 4), with the exception of d_{50} from the NIOSH laboratory #2 at 9.5 L/min; it might be considered as an outlier. The d_{50} values from the empirical model of the GK family were noticeably larger (up to 1 μm difference) than the d_{50} values from experimental data. The empirical models were obtained with experimental data of the GK1.52, GK1.52X, GK2.54, GK2.69, and GK3.45 and were limited to fixed geometry (cyclone body diameter) and flow rates.[12] A recommended flow rate of the GK4.162 cyclone from the model is at 10 L/min for respirable size-selective sampling. The model may not be extended to the Reynolds number of the GK4.126 cyclone operated at approximately 9 L/min.

To compare sampling efficiency between the laboratories, each sampling efficiency was replotted in normalized particle size (Figure 9) following the method introduced by Lidén and Gudmundsson.[31] A dimensionless particle size (Ξ), related to measured d_{50}, was used to normalize the diameter to force a 50% sampling efficiency for Ξ = 0. The Ξ was calculated by the following equation:

$$\Xi = \frac{\sqrt{C_c[d_{ae}]d_{ae}}}{\sqrt{C_c[d_{ae,50}]d_{ae,50}}} - 1, \quad (2)$$

where C_c is the Cunningham slip correction factor.[23] The data from the HSL and NIOSH laboratory #2 collapsed on the same curve whereas the data from the NIOSH laboratory #1 were slightly different. The difference might be attributable to the different experimental set-up and data analysis process.

Based on the results from the laboratories the recommended cyclone flow rate is at 9 L/min. This finding was confirmed by a previous study of respirable dust mass concentration comparison carried out by Stacey et al.[32] They reported respirable dust mass concentration ratios of the GK4.162 cyclone to the Safety in Mines Personal Dust Sampler (SIMPEDS; Higgins-Dewell design; standard respirable size-selective sampler in the UK and USA) when exposed to aerosols of Arizona road dust, coal dust and refractory mineral dust at different wind speeds. In 10 different experiments the average ratio of respirable mass concentrations between the GK4.162 and SIMPEDS cyclone was 1.04 and the GK4.162 cyclone was operated at a flow rate of 9 L/min.

A respirable size-selective sampler operating at a high flow rate including the GK4.162 cyclone tested in this study can be useful for quantifying RCS for more accurate 8 hr exposure assessment at low concentrations (<0.05 mg/m^3) and for shorter duration sampling. However, for the purposes of this investigation, task-based durations shorter than full-shift was of interest. The sampler can be useful in quickly evaluating the effectiveness of engineering control technologies that result in low RCS concentrations. It can be used to document compliance with occupational exposure limits for RCS in workplaces that have achieved effective silica dust control because the higher sample volume will provide an improved minimum detectable concentration given the same limit of detection and sampling duration.

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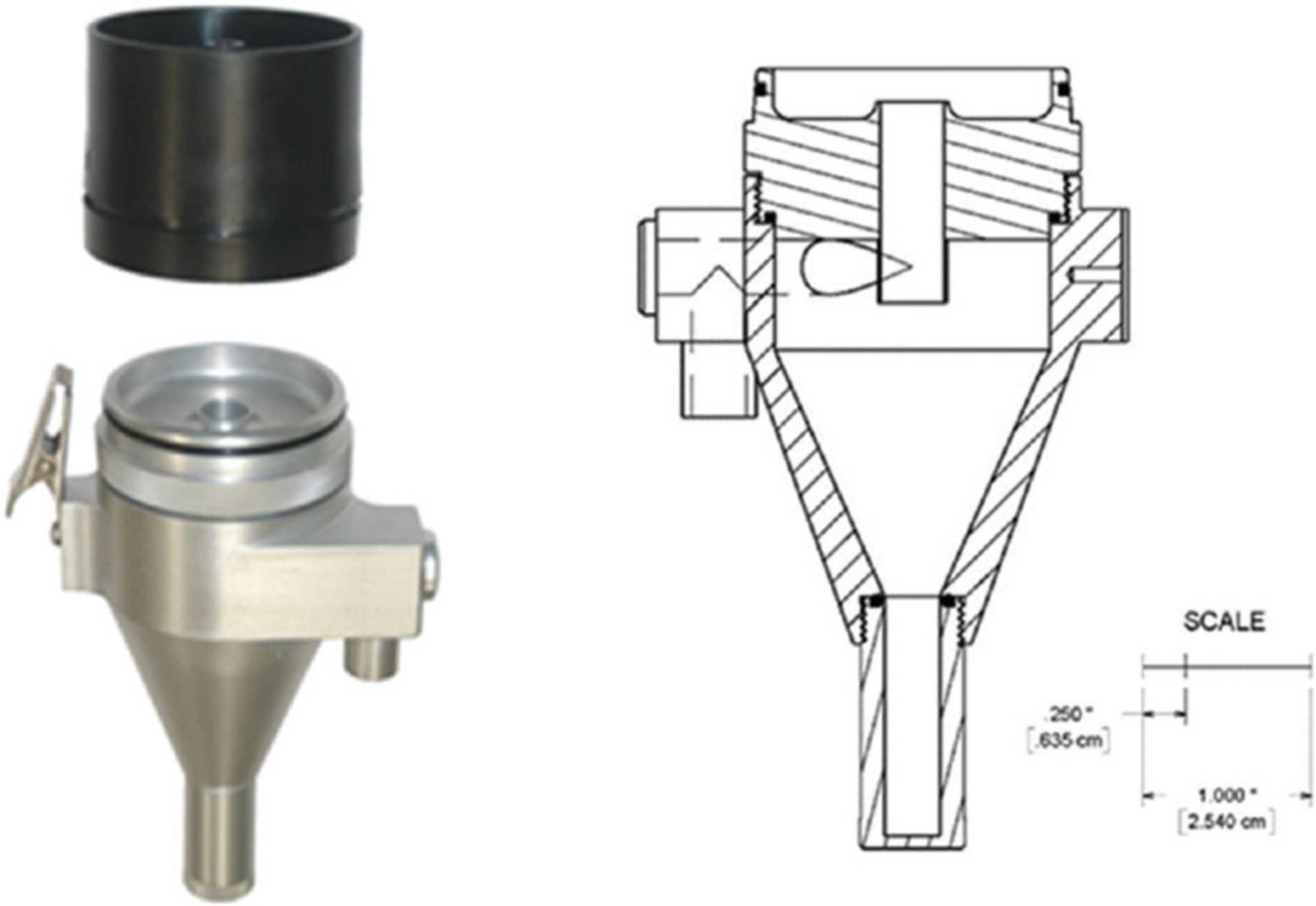

Figure 1.
GK4.162 cyclone and its cutway drawing (courtesy of BGI Inc.).

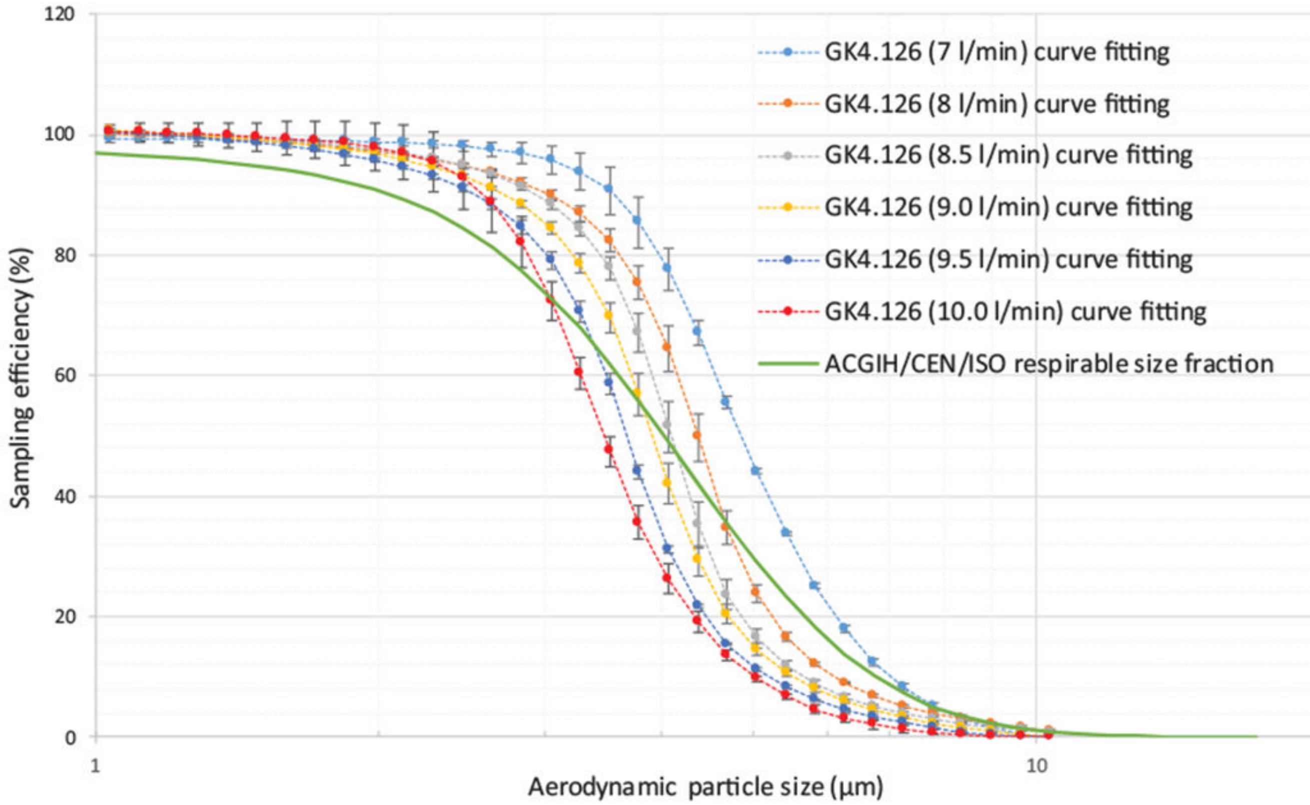

Figure 2.

Average sampling efficiency of the GK4.162 cyclone at six different flow rates (7.0, 8.0, 8.5, 9.0, 9.5, and 10.0 L/min) with polydisperse particles measured at the HSL (ACGIH/CEN/ISO respirable convention shown for reference). Error bars indicate standard deviation.

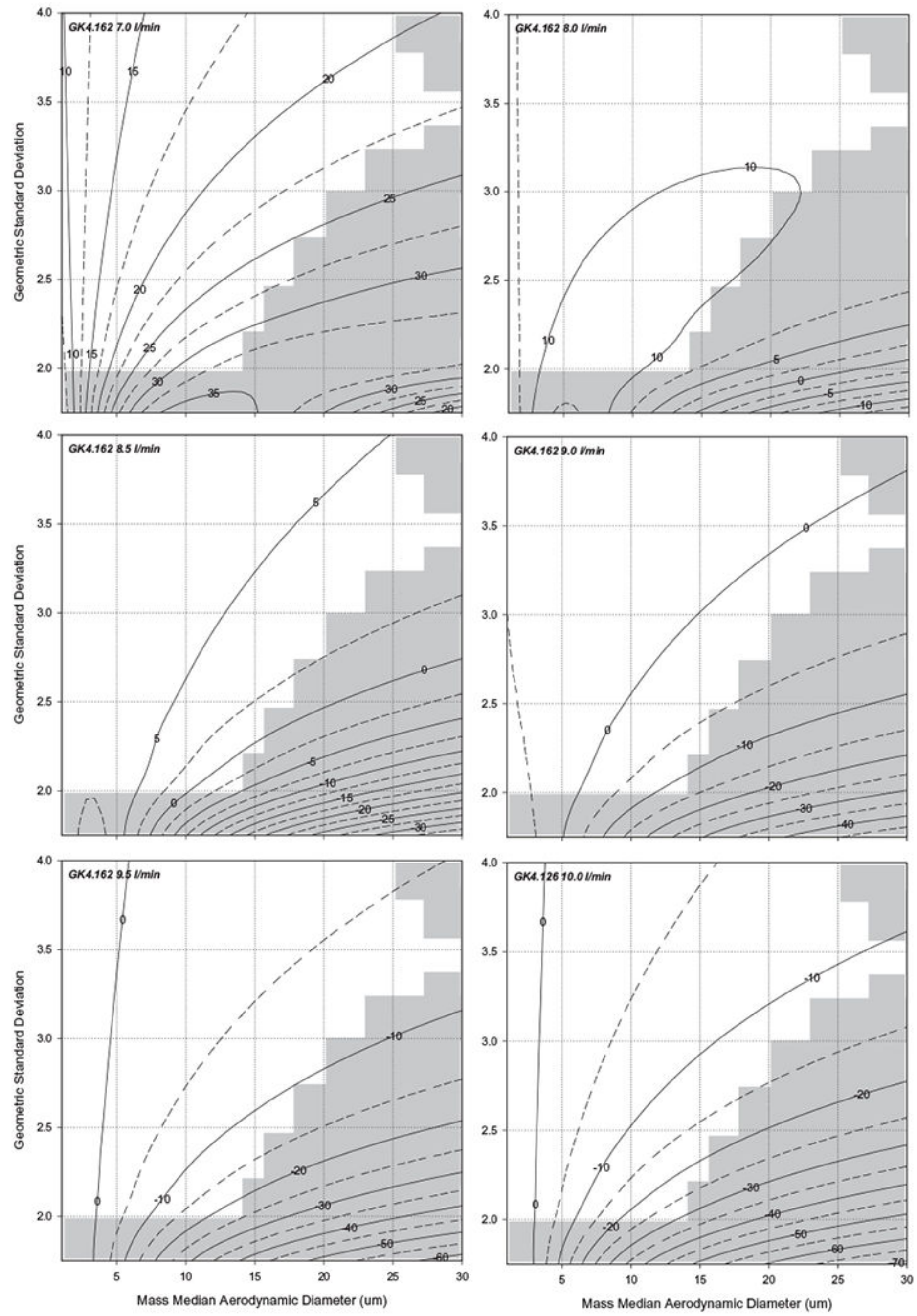

Figure 3.

Bias maps of measured GK4.162 cyclone performance at six different flow rates compared to the ACGIH/CEN/ISO respirable convention (Health and Safety Laboratory). Operation in the unshaded areas is desirable.

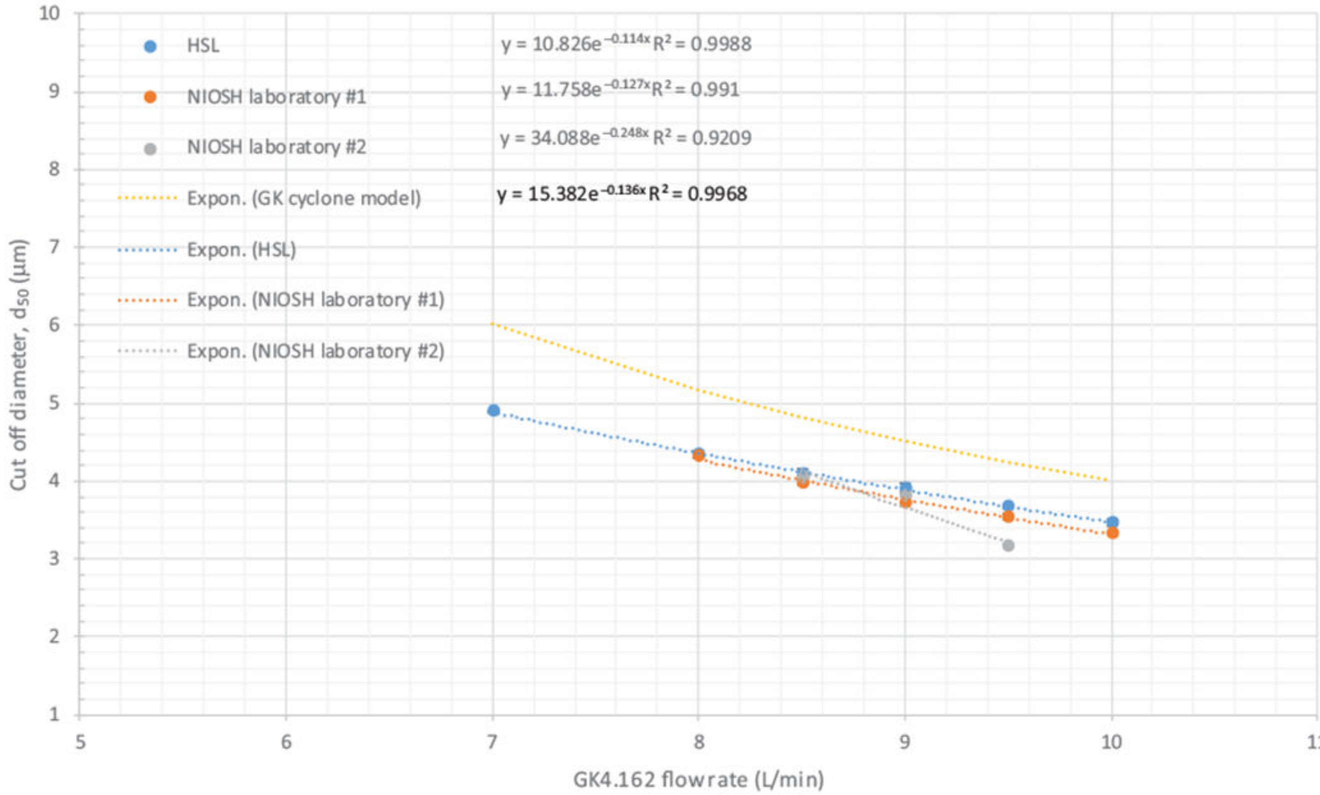

Figure 4.

Measured cut off diameter as a function of GK4.162 cyclone flow rate.

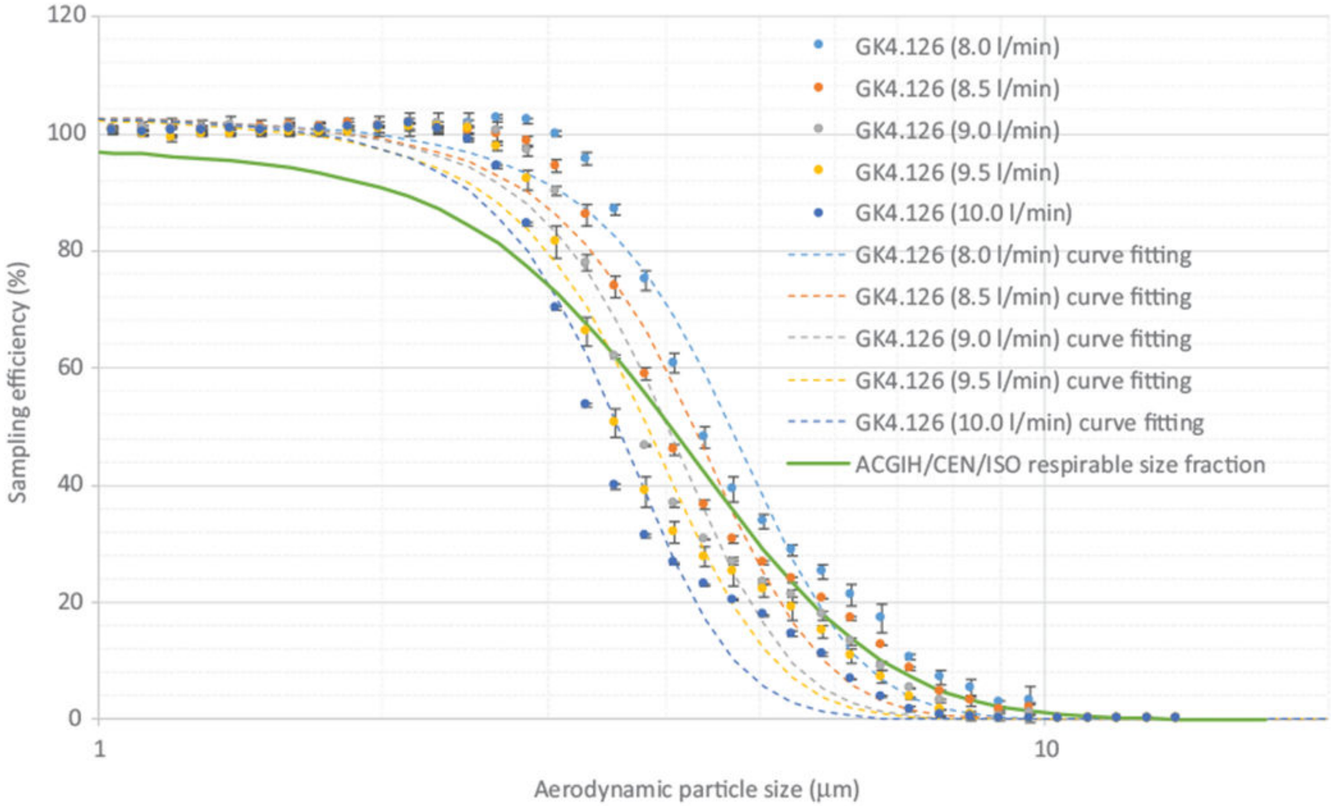

Figure 5.

Average sampling efficiency of GK4.162 cyclone at five different flow rates (8.0, 8.5, 9.0, 9.5, and 10.0 L/min) with polydisperse particles measured at NIOSH laboratory #1. (ACGIH/CEN/ISO respirable convention shown for reference). Error bars indicate standard deviation.

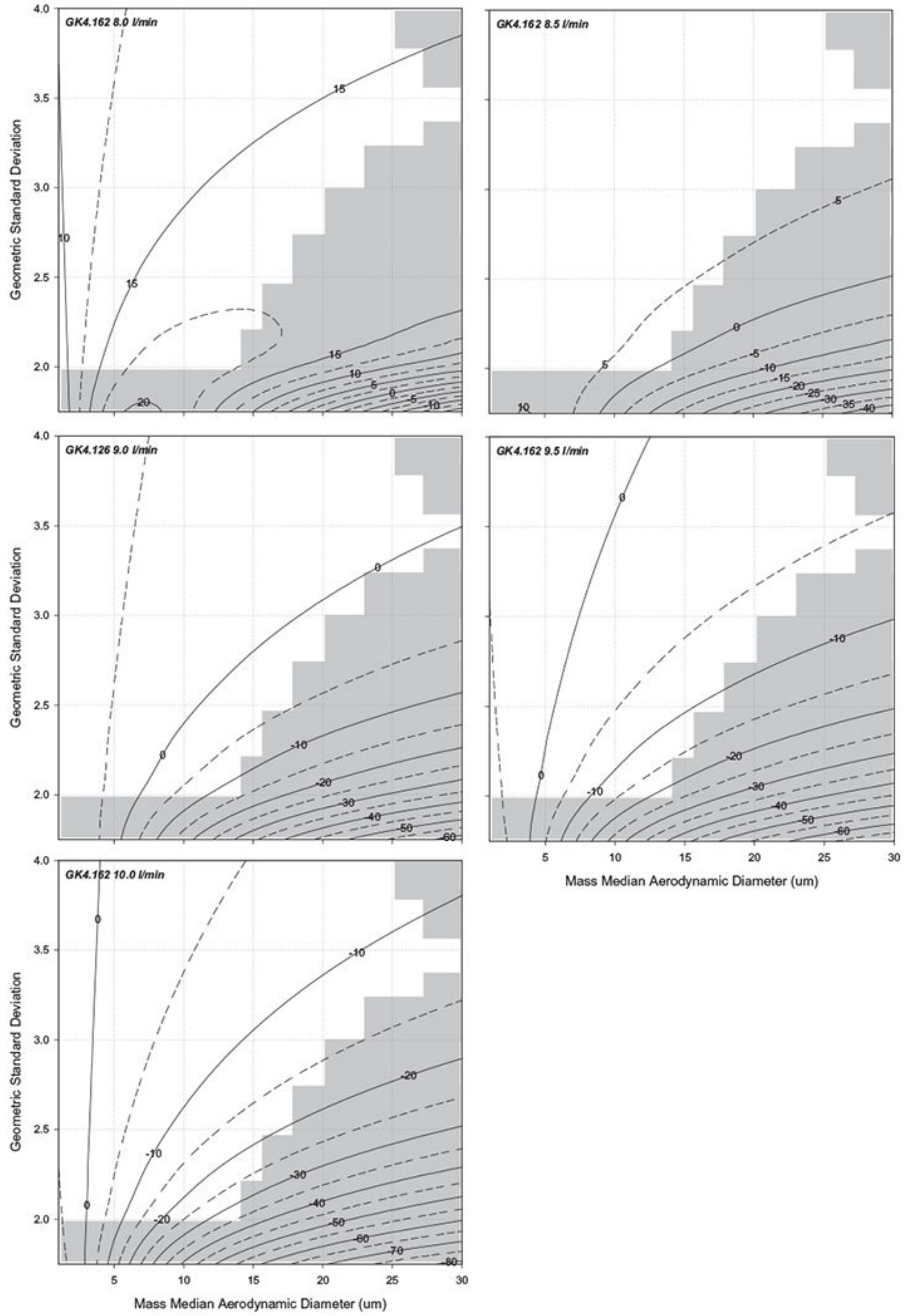

Figure 6.

Bias maps of measured GK4.162 cyclone performance at flow rates of 8.0, 8.5, 9.0, 9.5, and 10.0 L/min compared to the ACGIH/CEN/ISO respirable convention (NIOSH laboratory #1). Operation in the unshaded areas is desirable.

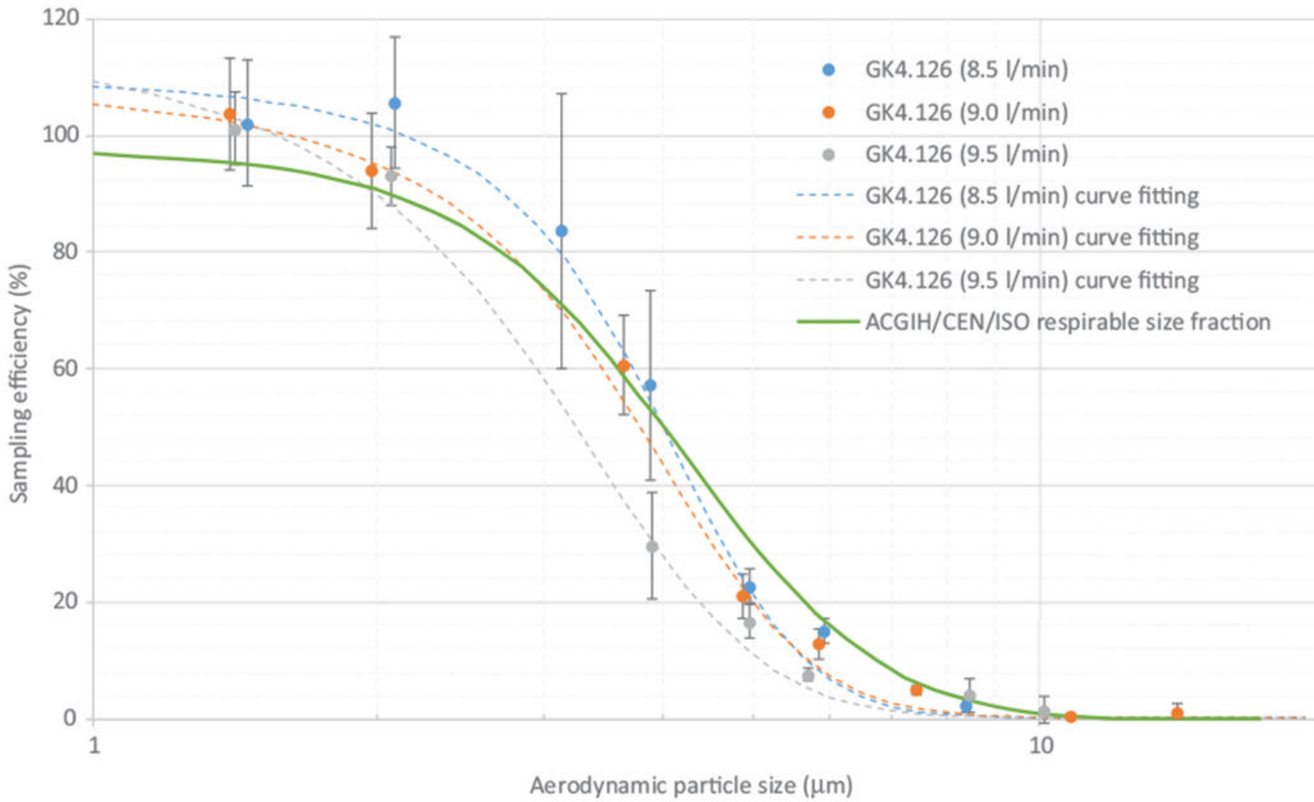

Figure 7.

Average and standard deviation of sampling efficiency of GK4.162 cyclone tested with monodisperse particles at flow rates of 8.5, 9.0, and 9.5 L/min (NIOSH laboratory #2).

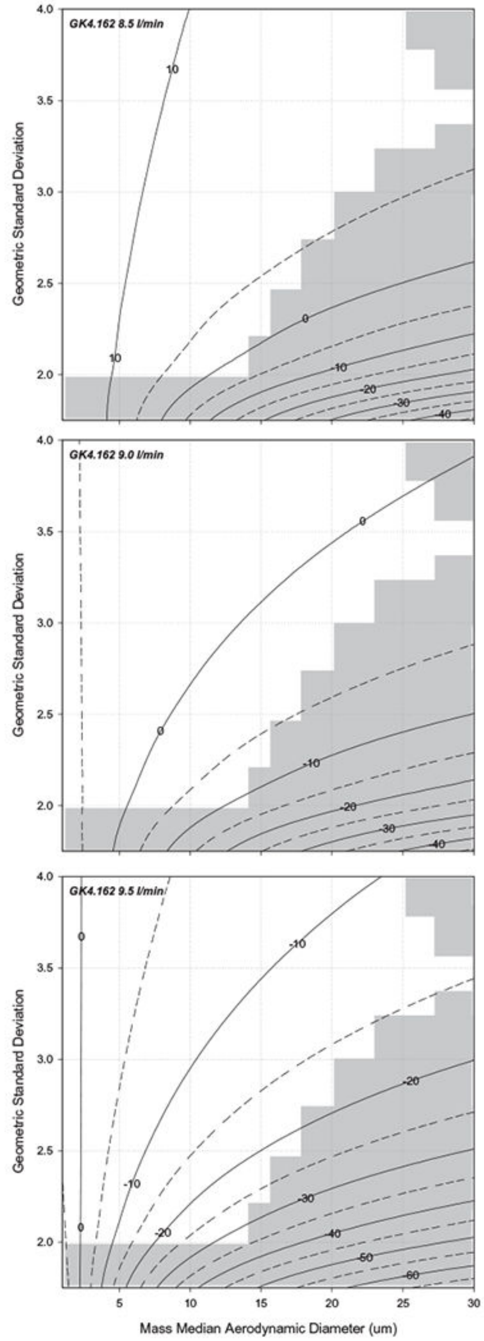

Figure 8.

Bias maps of measured GK4.162 cyclone performance at flow rates of 8.5, 9.0, and 9.5 L/min compared to the ACGIH/CEN/ISO respirable convention (NIOSH laboratory #2). Operation in the unshaded areas is desirable.

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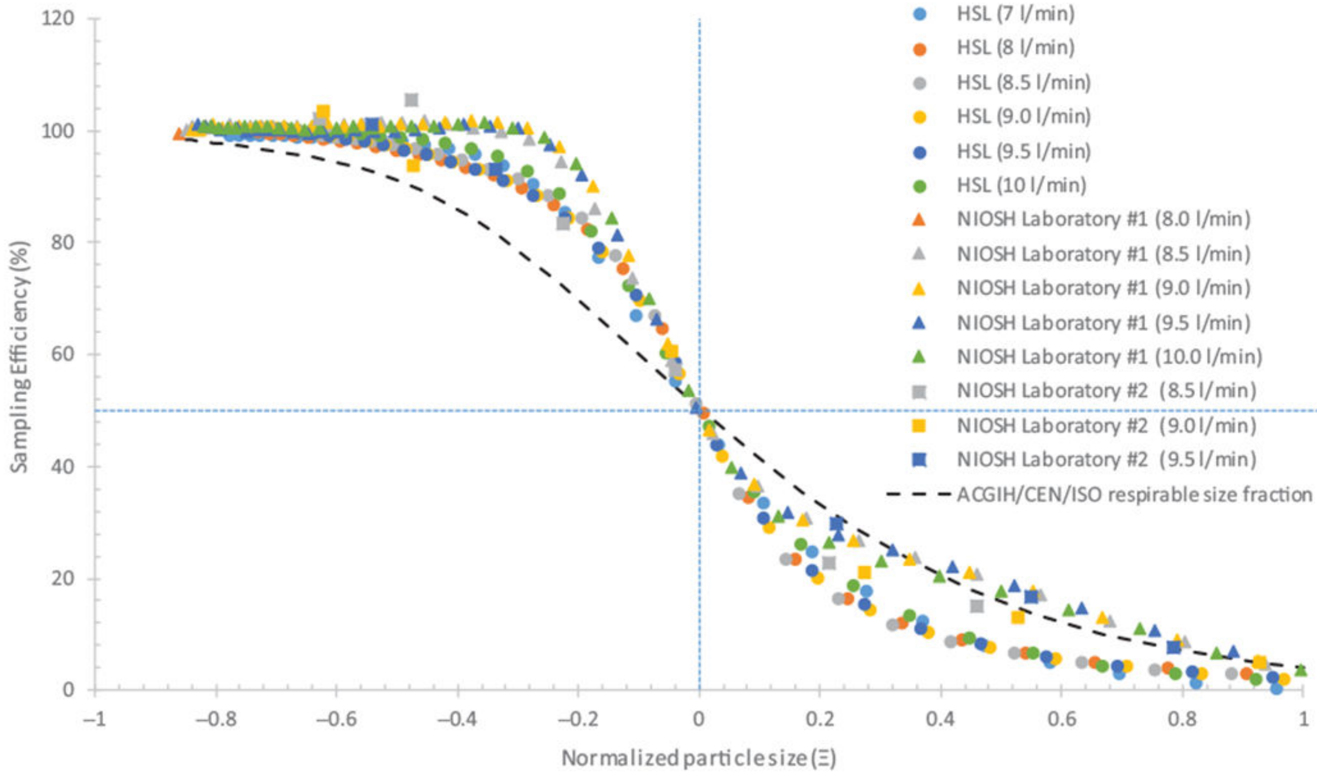

Figure 9.
GK4.162 cyclone sampling efficiency vesus normalized particle size (Ξ).