Differential Pressure Response of 25-mm-Diameter Glass Fiber Filters Challenged with Coal and Limestone Dust Mixtures

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This article summarizes results of research conducted by the National Institute for Occupational Safety and Health (NIOSH) at its Pittsburgh Research Laboratory. The objective of this work was to determine the correlation between the mass (M) of respirable coal and limestone dusts collected on 25-mm-diameter glass fiber filters mounted in cassettes and the increase in differential pressure (ΔP) that develops across the filters when drawing at constant air flow. Test aerosols were generated inside a laboratory dust chamber using various coal dusts, limestone dust, and mixes of the two. Dusts with different particle size distributions were deposited on the filters by sampling from the chamber through cyclone preclassifiers at different flow rates. Results show that the relationship between differential pressure increase (cm water) and dust mass (mg) is linear and can be approximated by the equation $\Delta P = KM$. The K values (slopes) range from 1.14 to 1.64, depending on the parent coal of the samples. The influence of particle size distribution was also found. The overall K value for all the data summarized in this article is 1.35, with $R^2 = 0.84$ for the summary equation. When calibrated for individual work sites, or other circumstances where great variability in dust characteristics is avoided, the relationship between collected dust mass and increase in differential pressure may provide an exploitable principle for measurement of respirable dust concentrations.

Keywords Dust Measurement, Dust Monitoring, Differential Pressure, Pressure Drop, Filters, Coal Dust

As the nation's mining industry moves into the twenty-first century, prevalence of occupationally related respiratory disease remains significant.(1) This long-term health hazard seriously compromises the well-being of mine workers and escalates healthcare costs. Preventing lung disease through reduction of worker exposure to injurious mine dusts is a shared priority for industry, labor, the Mine Safety and Health Administration (MSHA), and the National Institute for Occupational Safety and Health (NIOSH). Development of instruments that can rapidly measure the level of respirable dust in mining environments is a critical element for reduction of worker exposure. Such instruments could promptly reveal out-of-compliance dust conditions and expedite optimization of dust control strategies.

Presently, federal regulations require mine operators to regularly collect respirable dust samples using approved equipment and send them to an MSHA laboratory for gravimetric analysis.(2) There is a substantial time delay between collection of samples and their analysis, which is performed under controlled laboratory conditions at a location distant to the mine. Such delays both hamper the timely realization that excessive dust concentrations exist and impede adjustment of dust control systems to prevent high concentrations. The availability of a device for quicker assessment of respirable dust concentrations, simpler, more convenient, and less expensive than existing real-time monitors, would greatly help with these difficulties.

In 1992, an MSHA Respirable Dust Task Group recommendation provided new stimulus to investigate practical means of accomplishing on-site dust monitoring. This task group recommended that research be conducted to develop dust monitors "that will provide continuous information to the miner and mine operator on the status of dust resulting from the mining process as well as information on the status of compliance with respect to the applicable respirable dust standard."(3) The work described in this article addresses this recommendation to find a rapid on-site means of measuring airborne dust concentrations.

The focus of this research is the increase in differential pressure (ΔP) that occurs when a mass (M) of dust is collected on a sampling filter under constant air flow conditions, with greater dust masses causing greater differential pressure increases. This concept is straightforward and well recorded in the

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literature,$^{(4-12)}$ but interest has been in areas other than the effects of respirable mine dusts. The data collected in this study are derived from laboratory experiments using prepared coal dusts, limestone dust (commonly called rock dust), and coal-rock dust mixtures. The results provide a fundamental understanding of the performance of the ΔP method for estimating coal and rock dust masses on collection filters, clarifying whether the method could be used currently in some applications, and clarifying the method's potential with further instrument development.

This current research refines and expands substantially on an earlier study$^{(13)}$ of filter differential pressure, maintaining a focus on mine-related dusts (but relevant to all dusts). The earlier work by the authors used a limited variety of dusts over a limited range of dust deposit masses, investing substantial effort investigating alternative filter compositions. The primary conclusions of the earlier work were that glass fiber filters were the most useful of the compositions tried and that good correlations between dust mass and differential pressure increase were achievable. This article presents a new and more extensive study with a more advantageous filter material.

METHOD AND MATERIALS

Experimental Setup and Procedures

All experiments were conducted under laboratory conditions using the following general procedures:

1. 25-mm-diameter glass fiber filters were weighed, mounted on cellulose support pads, and then sealed in cassettes.
2. The initial differential pressure across each cassette was measured on a laboratory differential pressure apparatus at a 2 L/min flow rate prior to collecting any dust.
3. Each cassette was inserted in a sampling train between a 10-mm-diameter nylon cyclone and a constant air flow pump. Completed assemblies were then installed inside a 0.1-m^3 aerosol test chamber.
4. A dust mixture was selected and injected into the test chamber using a mechanical dust mill and dry pressurized air from a high-volume laboratory-scale compressor. The resulting dust-laden atmosphere inside the chamber was < 10 percent RH, necessarily dry to prevent the dust mill from clogging. To verify that the dust mill was functioning properly, a RAM-1 real-time aerosol monitor (manufactured by MIE, Inc., Billerica, MA) was used as a rough indicator of the dust concentration being generated.
5. Dust from the test chamber was sampled through the cyclones onto the filters at flow rates of 1, 2, and 3 L/min for various lengths of time.
6. The dust-laden cassettes were removed from the test chamber, then the differential pressure was again measured on the laboratory differential pressure apparatus at a 2 L/min flow rate. Subtracting initial from final differential pressure yielded the differential pressure increase (ΔP).
7. The filters were removed from the cassettes and reweighed. The filters were not desiccated, but were equilibrated to ambient laboratory conditions.
8. Data tables were generated correlating differential pressure increase with dust mass for each filter. A commercially available software program was used to plot each regression equation and calculate the coefficient of determination (R^2) and other statistics.

Filters and Cassettes

The filters used (manufactured by Pallflex Products Co., Putnam, CT) were of glass fiber composition with polytetrafluoroethylene (PTFE) binder. These high-efficiency 25-mm-diameter filters were capable of retaining high dust mass loadings and were selected because they performed well in small pilot tests of a variety of filters. Each filter, with cellulose support pad, was installed in a three-piece clear polystyrene cassette with a 2-in extension (manufactured by Envirometrics, Charleston, SC).

Glass fiber filters with PTFE binder produced the most accurate gravimetric measurements among various glass fiber compositions. The 100-percent glass fiber filters used in the earlier study$^{(13)}$ were prone to minor weight loss, possibly from fiber breakage. Glass fiber filters with non-PTFE binder tended to adhere to plastic cassette surfaces and tear, also causing minor weight loss.

Laboratory Differential Pressure Apparatus

Figure 1 shows the laboratory apparatus, constructed of polyvinyl chloride tubing, used to measure the differential pressure across filters. Each filter being tested was connected in parallel with two instruments. The first was a Magnehelic direct-reading mechanical pressure gauge (manufactured by Dwyer Instruments, Inc., Michigan City, IN) having a magnetic linkage to a pointer on a scale. It had a resolution of approximately 0.25 cm water. The second device was a variable-capacitance pressure transducer (manufactured by Setra Systems, Inc., Boxborough, MA) with steel diaphragm and insulated electrode. This instrument had a voltage output that required a conversion to differential pressure with a resulting resolution of approximately 0.025 cm water. The two gauges were used for redundancy to reduce the chances of operator error when making measurements. Only the data from the second instrument was used in the tables and figures of this article.

A shunt valve (V1) was opened whenever the vacuum pump was turned on or off to eliminate pneumatic shock to the instruments and to avoid dust dislodgement from the filters. Otherwise, the valve was kept closed. A small bench-top dry-air generator provided air at < 3 percent RH, while the vacuum pump and critical orifice maintained the air flow at 2 L/min. Flow rates were confirmed with a Gilibrator soap-film air flow calibrator (manufactured by Sensidyne, Inc., Clearwater, FL).

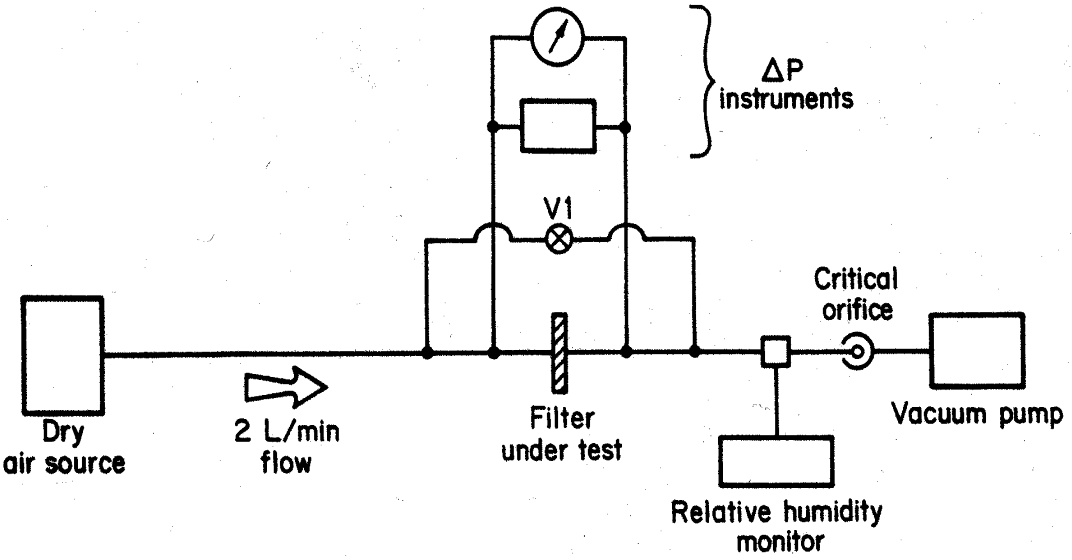

FIGURE 1

The laboratory constant air flow apparatus for measuring the differential pressure of filters.

Cyclone Performance at Different Air Flow Rates

The cyclones used in sampling from the test chamber were the Dorr-Oliver 10-mm-diameter nylon type used by the mining industry for collecting gravimetric dust samples to assess compliance with dust regulations. In these tests, the cyclones were used at 1, 2, and 3 L/min. Multiple samples were collected simultaneously at these three flow rates from each dust mix dispersed in the test chamber. Sampling flow rate and duration were the only differences in collection procedure between samples of a given dust mix.

The primary effect of different flow rates on cyclone performance is a shift in the 50-percent aerodynamic diameter cut size of the sampling efficiency curve.(14) If the flow rate is increased, the 50-percent cut size will decrease. For any specific particle size, the percentage penetrating through the cyclone will decrease as flow rate increases, reflecting the general increase in collection efficiency across all particle sizes. Conversely, decreasing flow rate will reverse these effects.

Thus, the cyclones at the different flow rates produced three different particle size distributions from the atmosphere generated within the dust chamber and deposited samples of the different distributions on different filters. Note that it cannot be assumed that the proportion of coal to rock dust collected on the filters was precisely the same as that in the atmosphere of the dust chamber. This is because the initial particle size distributions of the rock dust and the individual coal dusts are likely to be dissimilar, and a cyclone would act on the two dust fractions differently. However, because coal dust is extremely dark in color and limestone is extremely light, the shading of the filter samples served to confirm that their compositions roughly represented those of the bulk dust mixes used.

Dust Types

Dusts prepared from Black Creek, Illinois No. 6, Pittsburgh, Pocahontas No. 4, and Upper Freeport bituminous coal seams were used in this research. These dusts were ground and screened to −325 × 0 mesh. For tests not using pure unmixed dusts, coal-rock dust mixtures were created to achieve either 25-percent or 50-percent rock dust, by weight. Bituminous coals are recorded(15) as having a density of 1.35 ± 0.15 g/cm^3, and limestone as having a density of 2.50 ± 0.40 g/cm^3, almost double that of the coals.

TEST RESULTS

In agreement with the literature, research results indicate that the relationship between the increase in filter differential pressure and collected dust mass is linear and can be approximated by the equation:

$$\Delta P = KM \qquad [1]$$

where:

ΔP = differential pressure increase (cm water),
M = dust mass (mg), and
K = slope of the regression line.

Each regression line in this research may be regarded as an indication of continuous ΔP versus M filter response in that it is derived from a series of discrete measurements over continuous ranges for both ΔP and M. Each data point in the figures represents the ΔP for a single filter, corresponding to the collected dust mass M of that filter.

Figure 2, presenting a series of regression lines, compares the different dust family ΔP responses. Figure 3 shows the complete

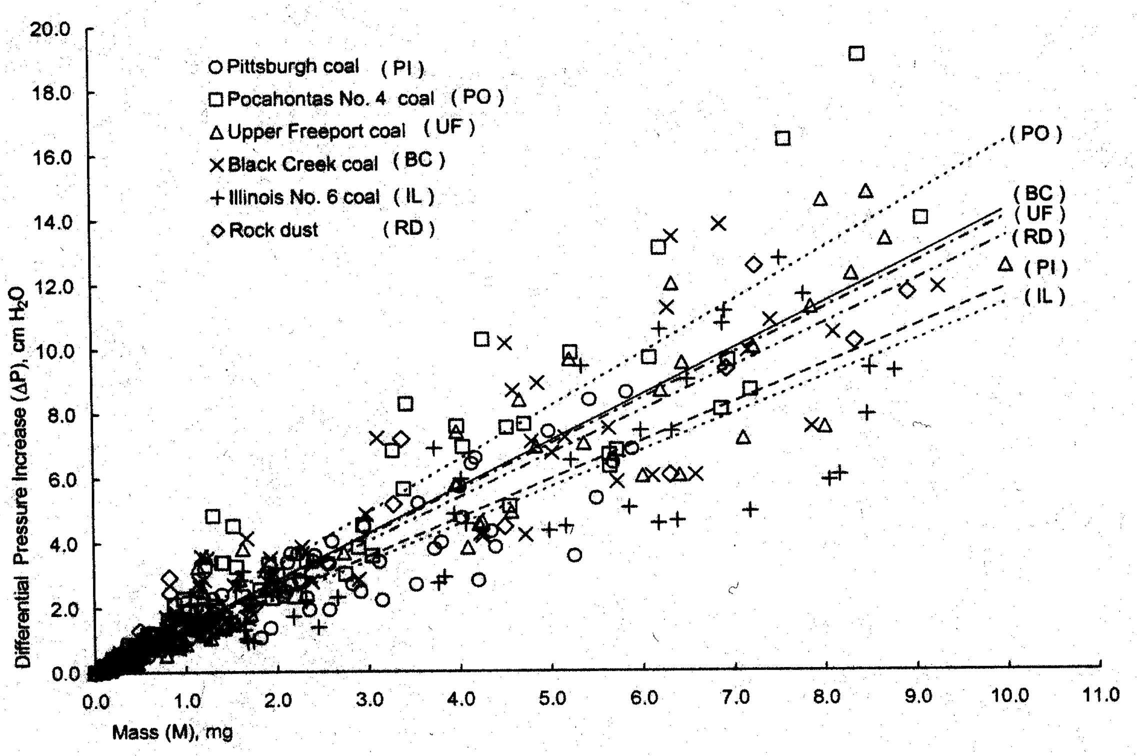

FIGURE 2
A comparison of the different dust family responses.

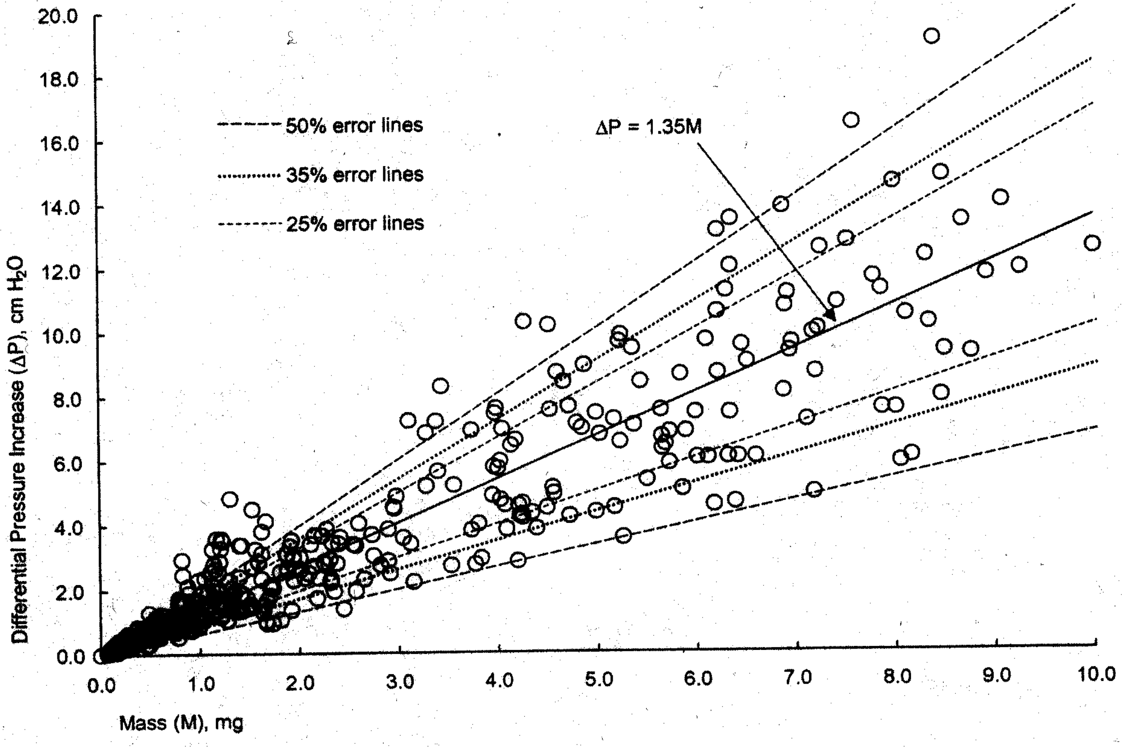

FIGURE 3
Regression for all data, $\Delta P = 1.35\ M$, bracketed by ±25%, ±35%, and ±50% lines.

TABLE I

Tabular summary of K and R^2 values for various types and sizes of data sets examined

Dust family	Coal-rock dust mixture: % Coal dust	Coal-rock dust mixture: % Rock dust	By flow rate within a mixture within a family: K_1 (R^2) 1 L/min	By flow rate within a mixture within a family: K_2 (R^2) 2 L/min	By flow rate within a mixture within a family: K_3 (R^2) 3 L/min	By mixture within a family K_M (R^2)	By family K_F (R^2)	By group K_G (R^2) and K_{G2} (R^2)
Black Creek	100	0	1.00 (0.99)	1.49 (0.99)	2.19 (0.99)	1.57 (0.83)		
	75	25	0.94 (0.99)	1.32 (0.99)	1.90 (0.99)	1.42 (0.85)	1.41 (0.85)	
	50	50	0.99 (0.98)	1.34 (0.99)	1.89 (0.96)	1.26 (0.90)		
Illinois No. 6	100	0	0.70 (0.99)	0.90 (0.94)	1.46 (0.99)	1.03 (0.82)		
	75	25	0.77 (0.96)	1.11 (0.98)	1.62 (0.98)	1.16 (0.82)	1.14 (0.81)	K_G (R^2)
	50	50	0.81 (0.98)	1.17 (0.98)	1.70 (0.99)	1.23 (0.84)		1.35 (0.84)
Pittsburgh	100	0	0.85 (0.95)	1.11 (0.98)	1.54 (0.98)	1.20 (0.87)		
	75	25	0.72 (0.96)	1.08 (0.97)	1.53 (0.99)	1.14 (0.82)	1.19 (0.85)	and
	50	50	0.93 (0.99)	1.19 (0.99)	1.53 (0.99)	1.27 (0.92)		
Pocahontas No. 4	100	0	1.11 (1.00)	1.61 (1.00)	1.97 (0.97)	1.67 (0.92)		K_{G2} (R^2)
	75	25	1.21 (0.98)	1.49 (0.94)	1.99 (0.90)	1.62 (0.86)	1.64 (0.88)	1.30 (0.94)
	50	50	1.23 (0.96)	1.39 (0.92)	2.10 (0.97)	1.66 (0.87)		
Upper Freeport	100	0	0.95 (0.99)	1.30 (0.99)	1.51 (0.98)	1.27 (0.93)		
	75	25	1.05 (0.99)	1.46 (0.99)	1.78 (0.99)	1.45 (0.92)	1.40 (0.91)	
	50	50	1.07 (0.96)	1.45 (0.99)	1.84 (0.99)	1.53 (0.92)		
Limestone	0	100	1.01 (0.97)	1.35 (0.98)	1.51 (0.91)	1.35 (0.91)	1.35 (0.91)	

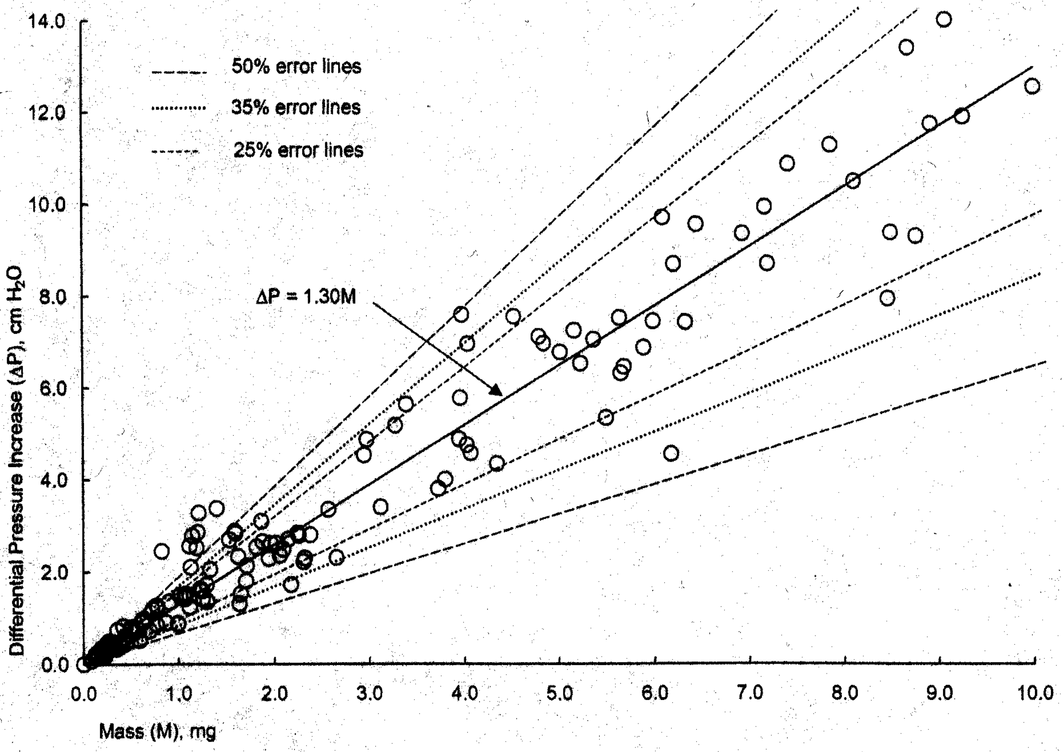

FIGURE 4

Regression for 2 L/min flow rate data, $\Delta P = 1.30\ M$, bracketed by ±25%, ±35%, and ±50% lines.

set of data from this research fitted with a single summary regression equation. In this composite case, $K_G = 1.35$ and $R^2 = 0.84$. Figure 4 shows the 2 L/min subset of the data, for which $K_{G2} = 1.30$ and $R^2 = 0.94$. This portion of the data was examined because cyclones are normally operated at 2 L/min. Table I lists K and R^2 values and is the primary tabular summary for all data gathered in this research.

Being the principal descriptor of differential pressure response, K values were calculated for many subsets of the data collected and recorded in Table I. When an integer, the subscript of K indicates sampling flow rate in L/min. The subscript "M" indicates "mixture." For purposes of this study, a pure dust is also considered a compositional "mix." The subscripts "F" and "G" indicate "family" and "group," respectively, while "G2" indicates "group 2L/min."

PREDICTING MASS BASED ON ΔP

The data points shown in Figure 3 represent the ΔP versus mass behavior for all of the filter samples generated and tested. If the three boundary conditions of ±25 percent, ±35 percent, and ±50 percent are used to bracket the line representing the regression equation $\Delta P = 1.35$ M, the percentage of data points within these three boundaries can be used as a measure of how accurately the equation can predict collected mass on the basis of measured ΔP. Figure 4, depicting the 2 L/min subset of the data, can be used in a similar manner, when its own regression equation is utilized.

Table II summarizes prediction accuracy based on this approach, derived from visual data point counts between error boundaries, performed on Figures 3 and 4 for masses above 2.00 mg. For the set containing all the data collected from highly variable dusts, error limits of ±50 percent are required to achieve a data point count with 93 percent inside the stated boundaries. Meanwhile, for the 2 L/min data subset, containing samples with somewhat less variability, narrower error limits of ±35 percent are required to achieve a similar data point count with 95 percent inside the stated boundaries.

TABLE II

The percentage of data points that fall within ±25%, ±35%, and ±50% of the values predicted by two linear regression equations representing all of the data, and the 2 L/min subset of the data[A]

	Percentage of data points bounded by the error limits applied to each equation	
Error Limits	$\Delta P = 1.35$ M (All data)	$\Delta P = 1.30$ M (2 L/min subset)
±25%	58	86
±35%	78	95
±50%	93	100

[A] For data with masses above 2.00 mg.

TABLE III

Summary of three-composition K_2 statistics

Dust Family	Mean K_2	K_2 Std. Dev.	CV (%)
Black Creek	1.38	0.093	6.7
Illinois No. 6	1.06	0.142	13.4
Pittsburgh	1.13	0.057	5.0
Pocahontas No. 4	1.50	0.110	7.4
Upper Freeport	1.40	0.090	6.4

Table III concentrates on the results for 2 L/min samples, broken down by dust family, rather than the full data set. It records the mean K_2 value for the three dust mixes in each dust family, as well as standard deviation and coefficient of variation (CV). It is noteworthy that the largest CV in the table is a modest 13.4 percent, derived from the Illinois No. 6 data.

GENERAL DISCUSSION

Despite its greater density, it can be seen in the K_M column of Table I that rock dust still has a ΔP response comparable to the other materials tested. $K_M = 1.35$ for 100-percent limestone dust, higher than K_M for pure Illinois No. 6, Pittsburgh, and Upper Freeport coals, but lower than K_M for pure Black Creek and Pocahontas No. 4 coals. This suggests that density is not the major factor that determines the magnitude of a dust's ΔP response. Table I records that the range of K_M for pure coals is 1.03 to 1.67. When the mixtures are 50-percent rock dust, substantially increasing the density of the test dusts, the range for K_M is 1.23 to 1.66, only moderately changed. This also suggests that the presence of rock dust, with the attendant effect on dust density, is not the predominant factor influencing ΔP response.

Further examining Table I for the influence of rock dust on ΔP, we find that adding the denser material to coal dust can change the coal's K value, but the trend is not always reliable. K_M for Black Creek coal is lowered as rock dust is added from 0 percent to 50 percent, while K_M for Illinois No. 6 and Upper Freeport coals rise as rock dust is added. K_M for Pittsburgh and Pocahontas No. 4 coals do not show clear trends as rock dust is added to their mixes. While the presence of rock dust is not without some consequence, the nature of the coal dust seems to have greater influence on ΔP response.

Table I shows that $K_1 < K_2 < K_3$ is a highly consistent trend, with the same influence of particle size distribution for every dust mixture tested. Smaller particles produce greater ΔP responses per unit mass than larger particles. The average K_1 value reported in Table I is 0.96. The average K_2 value is 1.30, 35 percent greater, and the average K_3 value is 1.75, 82 percent greater. For several of the dust mixtures tested, K_3 is more than twice the value of K_1. Particle size strongly and consistently influences ΔP response, regardless of the specific dust mix involved. The strong impact of particle size distribution and the weaker influence of density are generally recognized in the literature.(4,6,8–12)

The R^2 values recorded in Table I provide evidence as to what is required for a dust to be accurately measured by a ΔP-based instrument. Generally, R^2 entries trend lower as we progress from the left side of the table to the right. R^2 values are very high for a specific dust mix sampled at a specific flow rate. Most of the R^2 values that are both mixture- and flow-specific are 0.97 and above. The behavior of R^2 is not surprising. The variability in the dusts examined directly affects the variability in the data collected and their associated statistics. Dusts with less variability in particle size distribution, composition, and density will have more consistent filtration properties. Thus, the more consistent dusts are in these characteristics, the more predictable their ΔP response will be and the more accurately they will be measured by a ΔP-based instrument. Table II shows some of the limitations of the ΔP approach when highly variable dusts are involved. Applying only one regression equation to such dusts necessitates error boundaries of 35 percent or 50 percent.

Table III gives evidence for what is likely the best application of the ΔP method. Even though there is still a significant degree of variability in dust composition, limiting the data set to 2 L/min samples and breaking it down further by individual coals greatly improves the prospects for accuracy. Table III, whose highest CV entry is 13.4 percent, suggests that there are individual work sites where a ΔP-based instrument might be implemented usefully. It also suggests that a site-by-site calibration is necessary, unless it has previously been established that sites have very similar dusts. The ΔP approach appears robust for minor dust variations that may occur at the same work site, but is less reliable for major variations, or for variations occurring from one work site to another.

SUMMARY AND CONCLUSIONS

Experiments were conducted to measure the correlation between the mass of respirable dust collected on 25-mm-diameter glass fiber filters and the increase in differential pressure that develops across the filters when drawing at a constant air flow. Test atmospheres were generated inside a laboratory dust chamber using various coal dusts, rock dust, and mixtures of coal and rock dust. Deposits with different particle size distributions were collected on the filters by sampling the dust in the chamber through cyclone preclassifiers at different flow rates.

Results show that the correlation between differential pressure increase (ΔP) and dust mass (M) is linear and can be approximated by the equation $\Delta P = KM$, confirming work of other researchers. Observations on strong particle size influence and weaker dust density influence on ΔP also confirm the literature. This study's K values range from 1.14 ($R^2 = 0.81$) for the Illinois No. 6 family of dust mixtures to 1.64 ($R^2 = 0.88$) for the Pocahontas No. 4 family of dusts. The overall K value for all the data summarized in this article is 1.35 ($R^2 = 0.84$). These values describe trends for coal dusts derived from different seams, mixed with differing amounts of rock dust, and having different particle size distributions.

Correlations between ΔP and M for specific dust mixes sampled at specific flow rates are very high, with R^2 typically 0.97 and above. While K and R^2 are influenced by variability in dust composition and particle size, these factors will be more limited for any one work site than for a collection of many work sites. Therefore, prospects for dust measurement accuracy will be much improved when calibration is performed for an individual work site. A simple device for end-of-shift measurements can currently be constructed from common, commercially available hardware. A device for automated periodic or continuous dust concentration readings requires further hardware development. When a suitable portable instrument is developed, the device would also likely have its most accurate application when calibrated for specific dusts or individual work sites. Research toward such a ΔP-based continuous monitoring device is ongoing in our laboratory.

DISCLAIMER

Reference to any company name or product does not constitute endorsement by the National Institute for Occupational Safety and Health.

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