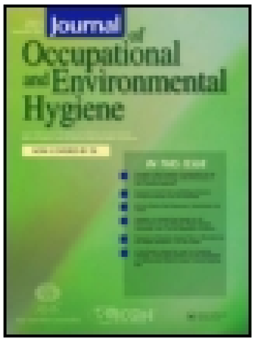

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Comparison of coarse coal dust sampling techniques in a laboratory-simulated longwall section

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ABSTRACT

Airborne coal dust generated during mining can deposit and accumulate on mine surfaces, presenting a dust explosion hazard. When assessing dust hazard mitigation strategies for airborne dust reduction, sampling is done in high-velocity ventilation air, which is used to purge the mining face and gallery tunnel. In this environment, the sampler inlet velocity should be matched to the air stream velocity (isokinetic sampling) to prevent oversampling of coarse dust at low sampler-to-air velocity ratios. Low velocity ratios are often encountered when using low flow rate, personal sampling pumps commonly used in underground mines. In this study, with a goal of employing mine-ready equipment, a personal sampler was adapted for area sampling of coarse coal dust in high-velocity ventilation air. This was done by adapting an isokinetic nozzle to the inlet of an Institute of Occupational Medicine (Edinburgh, Scotland) sampling cassette (IOM). Collected dust masses were compared for the modified IOM isokinetic sampler (IOM-MOD), the IOM without the isokinetic nozzle, and a conventional dust sampling cassette without the cyclone on the inlet. All samplers were operated at a flow rate typical of personal sampling pumps: 2 L/min. To ensure differences between collected masses that could be attributed to sampler design and were not influenced by artifacts from dust concentration gradients, relatively uniform and repeatable dust concentrations were demonstrated in the sampling zone of the National Institute for Occupational Safety and Health experimental mine gallery. Consistent with isokinetic theory, greater differences between isokinetic and non-isokinetic sampled masses were found for larger dust volume-size distributions and higher ventilation air velocities. Since isokinetic sampling is conventionally used to determine total dust concentration, and isokinetic sampling made a difference in collected masses, the results suggest when sampling for coarse coal dust the IOM-MOD may improve airborne coarse dust assessments over "off-the-shelf" sampling cassettes.

KEYWORDS
Aerosol sampling methods; coal dust; float dust; IOM sampler; isokinetic; large particle

Introduction

Since 1970, disasters due to explosions in underground coal mines caused 201 deaths in the U.S. mining industry, including 29 deaths in a single mine explosion in 2010.[1] Explosive coal dust, mostly uncontrolled prior to deposition, should be inerted with rock dust such that its total incombustible content (TIC) is 80% or greater.[2] A 2010 National Institute for Occupational Safety and Health (NIOSH) study showed that from 2005–2008, as much as 28% of nearly 61,000 collected coal/rock dust samples did not meet the 80% TIC criteria.[3] To provide additional strategies for meeting TIC criteria, control systems are being developed for airborne coal dust removal.[4, 5] These systems are most often evaluated in mine airways where rock dusting is carried out and where airborne rock dust is present.[4, 6] The confounding presence of airborne rock dust in coal dust samples has been addressed by low-temperature ashing (LTA) of filter samples using a stainless steel Institute of Occupational Medicine (IOM) cassette with quartz-fiber media.[7] With this method, coarse coal dust masses can be determined in mixtures of limestone rock dust in filter samples collected for control technology assessments.

In addition to the presence of airborne rock dust, a challenge of control technology assessments in the field is the collection of representative samples in high-velocity mine ventilation air. About 25 years ago, airspeed on coal mining longwall sections was rarely above 2.8 m/s, but significantly higher speeds, sometimes beyond 4.1 m/s, are currently used to dilute methane and diesel emissions below permissible exposure limits to meet state and federal regulations.[8, 9] As production rates continue to

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advance, the need for higher quantities of dilution air increases.[10,11] These higher air velocities allow large particles to remain suspended and increase the probability of distorting the size distribution during particle collection, and biasing the mass concentration estimate.[12] Attempts to avoid distorting the size distribution are made through isokinetic sampling, in which (1) the sampler inlet velocity is matched with the free-stream air velocity, and (2) the sampling probe is aligned parallel to air streamlines.[12] For turbulent conditions characteristic of high-velocity mine air, isokinetic sampler performance may not be affected by turbulence for sampling probes with sharp-edge inlets.[13] However, blunt inlets may decrease aspiration efficiency for large particles, especially those above 40 µm.[13]

Large particle sampling is of interest since this size range can contribute to dust explosion hazards. This is indicated by measurements of dust lean flammability limit as a function of dust diameter and coal rank.[14] For bituminous coal with high volatile matter content, particles up to 90 µm may contribute to ignition of an explosion, while for bituminous coal with low volatile content, particles up to 50 µm may contribute to explosion ignition.[14] Such large particles can remain airborne in mine ventilation air and may be sampled downstream of a coal mining longwall shearer. This was shown previously through isokinetic sampling and analysis of particles collected in a cyclone grit pot.[15] Mean diameter measured downstream of a longwall shearer was 15–35 µm, and the diameter below which 90% of the mass resided ranged from 33–372 µm for three Australian coal mines.[15] In the previous study, isokinetic sampling was carried out by adjusting sampler flow rate using an ejector pump operated by compressed air. However, use of compressed air to operate samplers may limit the location and/or number of sampling stations in an underground mine. These constraints can be alleviated by employing portable, low flow rate, personal sampling pumps, which are often used in occupational hygiene applications.[16] Personal sampling pumps are battery operated and do not require routing power to sampling stations. In addition, some are approved for use in underground mines due to intrinsic (non-spark generating) safety. Although there are several advantages, personal sampling pumps offer limited flow rates. To address flow rate constraints, interchangeable inlet nozzles were previously used, so that sampler inlet velocity could be matched to the free-stream air velocity.[17] Thus, a sampler that has a variable inlet diameter and that is operated by a personal sampling pump can facilitate ambient dust measurements for control technology evaluations in underground mines. When referring to particles or airstreams, "ambient" is used to represent the total airborne particles without size selection.

In total, representative dust concentrations most likely cannot be measured using personal samplers designed for inhalable dust collection. This is because inhalable samplers have been developed to meet international conventions for the fraction of the total aerosol which is inhaled as function of diameter.[18] Ambient dust sampler evaluations require a stationary platform that is aligned facing the flow and isokinetic sampling.[12,19] In contrast, inhalable dust samplers are evaluated using a rotating mannequin and flow rates mimicking breathing patterns.[20, 21] However, both types of sampler evaluations benefit from establishing uniform dust concentrations so that samplers can be challenged with similar aerosol, and side-by-side comparisons can be made.[21, 22] This is usually done in a wind tunnel under controlled conditions, which are especially challenging to establish for coarse particles due to gravitational, inertial, and turbulent diffusion effects.[23] Without well-controlled conditions, temporal and spatial changes in concentration can complicate sampler comparisons.[21, 22]

This study was conducted to determine if the use of a near-isokinetic sampler was necessary for sampling coarse airborne coal dust in high-speed airflows, or if commercially available (anisokinetic) sampling cassettes produced similar results. For replicate tests, a coefficient of variation of less than 10% would indicate that the sampler was adequate for field sampling, since the sampler would be used to demonstrate control technology effectiveness on the order of 30% or greater. (With less than 30% efficiency, a given control technology most likely would not be implemented.) Accuracy of the sampler in terms of aspiration efficiency (collected dust mass concentration divided by total airborne dust mass concentration) could not be determined since that would require a nearly-ideal isokinetic sampler with a sampling body that caused minimal disturbance to the flow streamlines and controlled wind-tunnel conditions in which aspiration efficiency could be determined as a function of particle diameter.

Specifically, the test was conducted to accomplish these two objectives.

1. Quantify the airborne dust concentrations in a simulated long wall mining test gallery to determine if the concentration gradients are low enough to permit side-by-side comparisons.
2. Determine if one of three sampler arrangements approximate the performance of the IOM-MOD for a range of feed dust sizes and airspeeds:
   i. IOM sampler;
   ii. standard coal dust cassette, no cyclone; and
   iii. standard coal dust cassette, no cyclone, orthogonal to flow.

Methods

Facilities and materials

Coarse coal dust sampling was carried out in a full-scale longwall gallery at the Pittsburgh Research Laboratory (Figure 1). The laboratory approximates the dimensions and airflows found in many underground longwall coal mining faces in the U.S. The length, width, and height of the gallery are 38, 6, and 3 m, respectively. A simulated Joy Mining Machinery 7LS shearer is located about halfway through the gallery, and 24 shield supports (1.5-m wide ea.) line the side of the gallery. Three centrifugal fans, driven by electric motors totaling 164 kW, are capable of inducing airflows of approximately 4 m/s. Air velocities were measured with a TSI hot-wire anemometer, model 9595. The anemometer was clipped into place on the sampling rack so that the sensing element was at the geometric center of the sampling area. Air velocity was well controlled with standard deviations of 0.01 m/s and 0.05 m/s for low and high air velocity, respectively. The flow in the experimental mine gallery was highly turbulent, with Reynolds number (Re) 1.4×10^5 and 7.6×10^5 for low and high air velocity, respectively.

Filter samples were gravimetrically analyzed in the Pittsburgh Mining Research Division (PMRD) Microbalance Laboratory, a 6- x 6- x 3-m facility (including airlock area) equipped with a recirculating Liebert HVAC system and HEPA filtration system to provide stable air conditions and temperature and humidity control for accurate weighing of filter samples. The weighing chamber houses several microbalances. Mylar control filters are used to monitor room and balance performance, and the standard filter mass was varied by less than 5 μg between analyses. A wide-resolution, high-accuracy, Mettler XP26 microbalance was used with a 26-g capacity and 1-μg resolution.

Two types of coal dust with different size distributions were used. The first is mostly composed of respirable dust and is often used by PMRD for dust control research—Keystone Mineral Black (Fine) 325BA, of which approximately 63% by volume is <10 μm. The second, larger dust, was custom-ground for NIOSH by Hadsell Chemical Processing (Waverly, OH), with 14% by volume <10 μm and a volume mean diameter of 53 μm. The Hadsell product was screened between 200-mesh and 400-mesh for 1 hr, which further focused its mean diameter between 38 and 75 μm. These size ranges are for bulk dust input to the dust disperser and may have changed after aerosolization and transport to the dust samplers. Because of study constraints, aerosol sizing instruments were not available, and computational fluid dynamic calculations for turbulent flow were not made to estimate the dust volume-size distribution at the sampling location. Although aerosol size distributions were not determined, greater mass concentrations were present at the sampling location for coarse dust than for fine dust. This was determined while free-stream air velocity (2.85 m/s) and mass rate from the dust disperser were fixed, which suggests larger particles were indeed in the coarse aerosol at the sampling location.

Establishing relatively uniform dust mass concentrations in the sampling zone was facilitated by maintaining stable conditions for the dust dispersion system. Dust was aerosolized from an auger feeder located outside the longwall gallery and introduced by compressed air through a hose with inner-diameter of 19 mm. Because the hose is flexible, an aiming nozzle was created which included a bore-scope laser that fixed the dust source position (Figure 2). The hose and nozzle assembly were firmly fixed to the lab infrastructure via a high-strength magnet. The location of the dust outlet was 7.3 m from the samplers, and its precise aim was indicated by the alignment laser and was kept constant throughout the testing.

Sampling system

A sampling rack and unique sampler mounts were designed and installed such that the filter-based samplers would be aligned with respect to the tunnel, which should help prevent anisokinetic sampling due to misalignment (Figure 3).[12] A maximum tolerance of 0.5° (horizontal and vertical angle) was maintained by rotational freedom about the Y and Z axis controlled with a double-pivoting tube clamp. The sampling rack was constructed out of T-slotted aluminum extrusions, and the rack's alignment perpendicular to the laboratory's normal flow direction was visually checked by an additional alignment bore-scope laser focused on an opposite wall some 23 m away. Airflow was adjusted with sliding dampers such that a hot-wire anemometer's 3-min average airflow, taken in the geometric center of the samplers, was within 5% of the target air velocity. The atmospheric conditions were such that temperature, humidity, and pressure were all within 2% of each other between tests.

Sampler types

In the selection and design of the samplers, consideration was given to use samplers that were commercially available to the mining industry. A number of practical considerations were taken into account, especially given the constraints of underground coal sampling, which presents unique challenges including the permissibility of instruments, the confounding influence of rock dust, and the often-limited number of samples possible due to mine access constraints. Given that the commonly available

Figure 1. Longwall gallery used for the experiments. Toward the end of the gallery, the sampling rack can be seen, especially the alignment lasers (shown as white stars).

sampling pumps approved for underground coal mines have a limited operating range (1.7–3.0 L/min) and are more commonly set up for sampling at 2.0 L/min, a practical way to match the airstream and inlet velocities is to utilize interchangeable nozzles with a common sampler body, this was done to adapt a personal sampler for isokinetic sampling. Four mine-compliant samplers (Table 1) described in what follows were co-located and aligned on the specialized sampling rack (Figure 3).

Table 1. Sampler description and inlet diameter.

Description	Abbreviation	Inlet ID (mm)
Institute of Occupational Medicine Personal Sampler	IOM	14.99
Modified IOM with Interchangeable Isokinetic Nozzle	IOM-MOD	3.86/9.40
Zefon Coal Dust Cassette	ZCD	5.05
Zefon Coal Dust Cassette (90 deg)	ZCD-90	5.05

The Institute of Occupational Medicine personal sampler, (IOM, inlet dia. of 14.99 mm) composed of conductive plastic, is the standard measure for compliance sampling of inhalable dust at surface operations and is typically hung from the shirt collar.[24] In the current study, the plastic IOM was fitted with a 25-mm glass fiber filter with a 1.0-µm nominal pore size and mounted facing and in-line with the flow. The IOM sampling cassette and filter assembly are weighed together, so that dust depositing on the walls is included in gravimetric analysis. Including wall deposits was shown to be especially important for large particles in previous studies.[24, 25]

The second sampler configuration (IOM-MOD) utilized a stainless-steel construction of the IOM along with a custom-designed and machined-interchangeable inlet configuration to allow for isokinetic sampling (Figure 4). Two stainless nozzles were designed, with inner diameters of 3.86 and 9.40 mm, for achieving isokinetic conditions

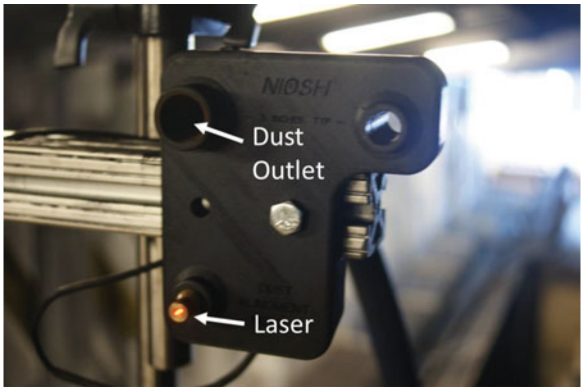

Figure 2. The dust release point was well controlled by use of a custom-manufactured "dust alignment nozzle" which utilized a gun-sight laser to ensure the repeatable aiming of the dust outlet. (The laser can be mounted in either the bottom left or top right hole, and the dust was released from the top left.)

under high (2.5 m/s) and low (0.5 m/s) free-stream air velocities, respectively. At least 5.6 diameters were maintained from the nozzle inlet tip to the filter media, and a 30° tapered "knife-edge" was cut onto the end of each nozzle. The tubing used to construct the nozzles was smooth bore type with a tolerance of +/− 0.15 mm. The interior of the custom 3D printer adapter was flared so that the dust was directed towards the filter. The plastic custom nozzle adapter was removable, leaving the stainless-steel filter capsule assembly to be ashed via the LTA method[7] so that coal and inerting rock dust fractions could be determined. An SKC quartz filter, type R-100 with a 1.2-µm nominal pore size, was used. Quartz was used rather than glass fiber (as in the plastic IOM), so that the sampling cassette was appropriate for LTA for the analysis of coal dust in mixtures with limestone rock dust.[7] The stainless steel cassette weighs several grams and requires a wide-resolution microbalance and controlled weighing conditions to accurately determine collected particle masses,[25] which were achieved through the weighing chamber facility and the sensitive microbalance described above.

The Zefon coal dust sampling cassette (ZCD, inlet size of 5.05 mm) is the industry standard for respirable coal dust sampling to meet compliance requirements (when using a size-selective cyclone on the inlet). The cassette is equipped with a 5-µm pore size PVC filter with a metal foil dome crimped to the filter perimeter. Large non-respirable particles pass through the short inlet at high velocity (1.66 m/s) and either deposit near the filter center, follow the flow radially in the zone between the foil and the filter, or settle due to gravity near the foil/filter junction. Because the dome and filter are weighed together, potential wall losses would be included in the mass measurement. The Zefon cassettes were mounted in two configurations: (1) directly in-line and facing the tunnel flow and (2) 90° to the flow and facing the tunnel floor, which is similar to the MSHA nuisance dust sampling method.[26]

Sampler arrangements

A two-plane sampling rack was designed so that its dimensions would be in a cross section of the available area, roughly centered to allow for some buffer between the roof, walls, and equipment mounted below (shearer body). The samplers were arranged on the rack such that the available area would be fully utilized (Figure 3). The between-sampler separation in the horizontal axis was 63.5 mm, and a set of four samplers occupied 190.5 mm. The quadruplicate sampling packages were then 374.7 mm between centers horizontally and 406.4 mm vertically. Each sampler was then attached to a vacuum line that was fed from a manifold; three such manifolds were utilized to provide the necessary vacuum for all 24 samplers. Each line's flow was recorded with a Gilibrator (Sensidyne, LP) before and after each test, and was maintained no more than 3% above or below the target flow rate of 2.0 L/m. The use of custom-machined 3D printed parts ensured that all samplers were accurately positioned relative to the airflow.

Spatial concentration variability

Fluctuations in air flow arise from equipment obstructions, stability limitations of the airflow controllers, pressure changes that occur within the larger building, and the atmospheric conditions. In addition, changes in the particle size distribution arise from inertial, gravitational, and turbulent diffusion effects. In order to study the cumulative effects on coal dust concentration variability, four tests were conducted—two before and two after the total test program. The intention was to (1) locate the minimum concentration gradient across the six sampling locations to facilitate side-by-side sampler comparisons and (2) to compare the repeatability between days, since test-to-test repeatability would enable performance of a given sampler to be evaluated. Approximately identical (±0.15 mm inlet diameter) IOM-MODs were utilized, with three units in each of the six different sampling locations (Figure 5). Each test was run for 20 min, with an air velocity of (2.85 ± 0.05) m/s and a mean dust feed rate of 1,135 g/hr (+/− 4.6%). The IOM-MOD inlet velocity was within 10% of the isokinetic sampling velocity given tolerances in the nozzle inlet diameter (±0.15 mm) and control of the laboratory air velocity (±0.05 m/s). All sampler inlets were capped just after the vacuum was removed at the conclusion of testing, transported to the climate-controlled weighing room, and allowed to

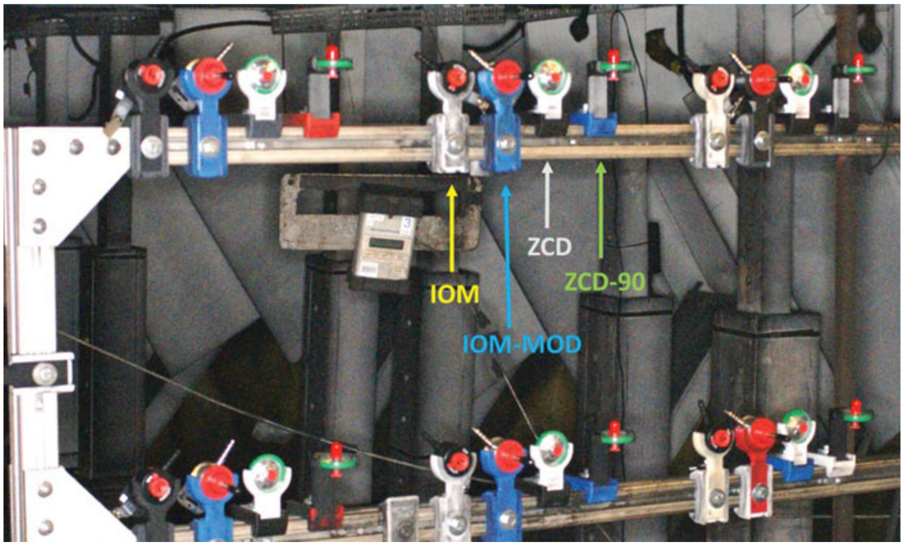

Figure 3. In each of the six locations, four samplers were compared. From left to right, IOM, IOM w/ isokinetic nozzle adapter (IOM-MOD), coal dust cassette (ZCD), coal dust cassette at 90° to airflow (ZCD-90). The IOM-MOD sampler had interchangeable nozzles that were matched to the free-stream air velocity.

acclimate for at least 12 hr. The time for IOM equilibration in the weighing chamber was found to be relatively short, probably because the weighing chamber relative humidity was maintained at 53%, which was near ambient conditions during sampling. The samples were then weighed and were blank corrected by 1.7% mean and 2.1% maximum (percentage of blank relative to the mass gain). Three blanks were measured for each sampler type (cassette and filter assembly).

Sampler comparison

The following variables were tested for the sampler comparison, and a summary of the test conditions is given in Table 2:

1. airstream velocity: 0.5 m/s, 2.85 m/s;
2. dust size: fine (63% by volume < 10 μm), coarse (14% by volume < 10 μm); and
3. sampler type: IOM, IOM-MOD, ZCD, ZCD-90.

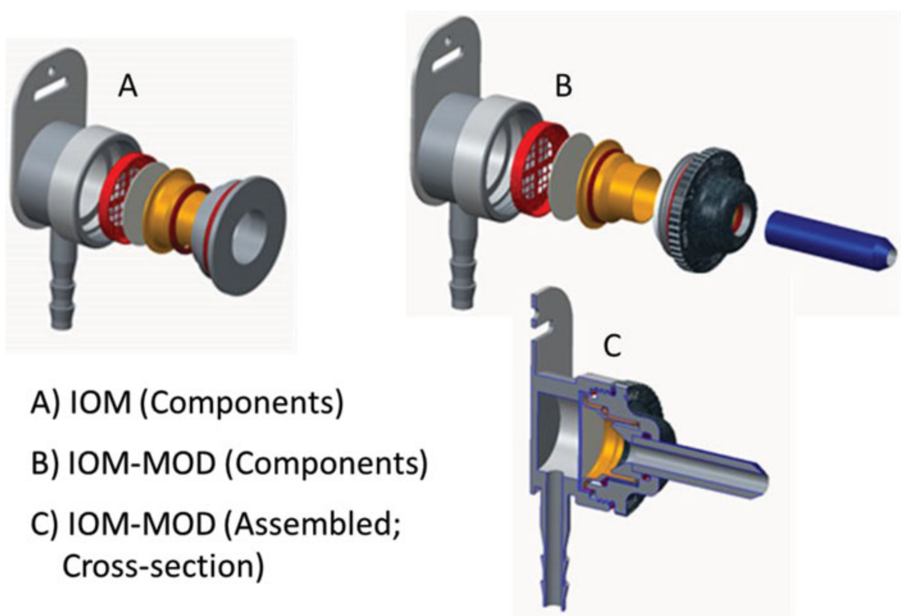

Figure 4. Original (A) and modified IOM (B,C) samplers. Sectional view (C) of the stainless IOM-MOD with custom nozzle/inlet combination. Nozzle is 38 mm long and constructed from tubing-grade stainless steel, and threaded adapter is 3D-printed and sealed with O-rings. Nozzle was kept short to minimize dust loss on interior.

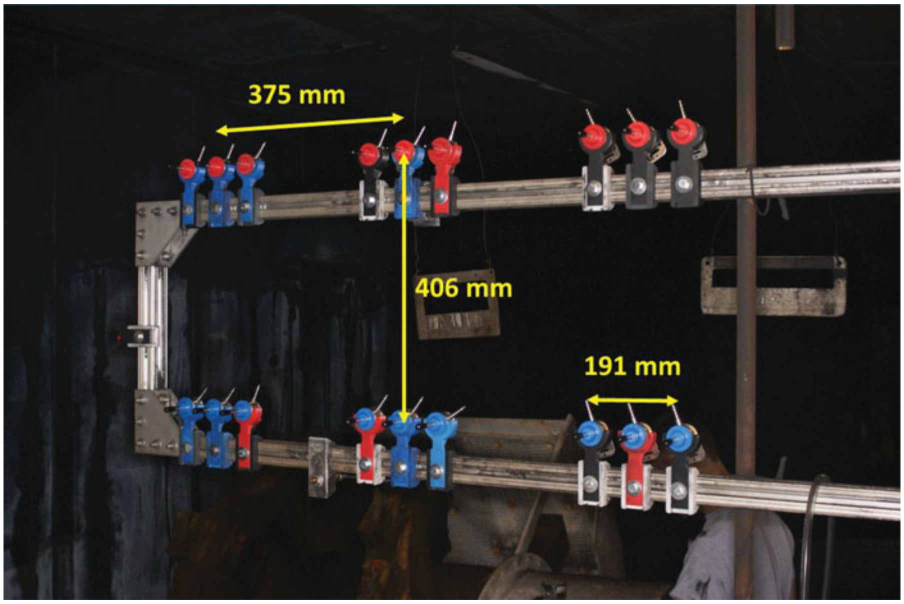

Figure 5. IOM-MOD samplers arranged in six locations across the sampling rack to measure the variability in dust concentration across the rack (top and bottom) as well as from test to test.

The IOM-MOD inlet nozzle was changed so that sampler inlet velocity could be matched to free-stream air velocity (within 10%). However, the IOM, ZCD, and ZCD-90 inlets remained the same for low and high air velocities. The sampler inlet to free-steam air velocity ratio was less than 1 (sub-isokinetic sampling; over-sampling ambient concentrations) at 0.5 m/s and 2.85 m/s for the IOM, and at 2.85 m/s for the ZCD. The sampler inlet to free-stream air velocity ratio was greater than 1 (super-isokinetic sampling; under-sampling ambient concentrations) at 0.5 m/s for the ZCD. The ZCD-90 had the same velocity ratios as the ZCD, but the ZCD-90 was additionally sampling anisokinetically, since the position was misaligned 90 degrees relative to the flow. The ZCD-90 position approximated the orientation of a cassette hanging from a worker's lapel during personal sampling for nuisance dust.[26] A summary of the velocity ratios for each sampler is given in Table 3.

Table 2. Side-by-side sampler study matrix; 2×2 matrix repeated once (bold font).

Air Velocity (m/s; Low / High)	Dust (Fine / Coarse)
High (2.88)	Fine
High (3.00)	Coarse
Low (0.46)	Coarse
Low (0.46)	Fine
High (2.89)	**Coarse**
High (2.90)	**Fine**
Low (0.48)	**Fine**
Low (0.48)	**Coarse**

Results and discussion

Spatial concentration variability

Dust mass concentration was measured across the sampling rack to determine whether relatively uniform concentrations could be established to facilitate side-by-side sampler comparisons. Each sampling location had three co-located IOM-MOD samplers (Figure 5), which were operated at 2.0 L/min, since this is the typical flow rate for permissible underground coal sampling pumps. The results of the concentration variability study (based on 4 tests with 18 samplers, and hence 72 total filter samples) show that a standard error of 2.5 mg/m^3 can be expected on either the top or bottom racks (Figure 6). The arrangement of the laboratory equipment (longwall shearer, panline, and roof supports) necessarily created large-scale turbulence, and the highest variability was seen on the bottom rack. The mean coefficient of variance (CV) was 24.0 and 10.2% for the bottom and top racks, respectively. At the top center location, the differ-

Table 3. Velocity ratios (Uo/UI) for each sampler at high and low air velocities.

Sampler	Low Velocity	High Velocity
IOM	0.4	0.1
IOM-MOD	1.0	1.0
ZCD	3.5	0.6
ZCD-90	3.5	0.6

Note. UO = Free-stream air velocity outside sampler inlet; UI = Mean air velocity inside sampler inlet.

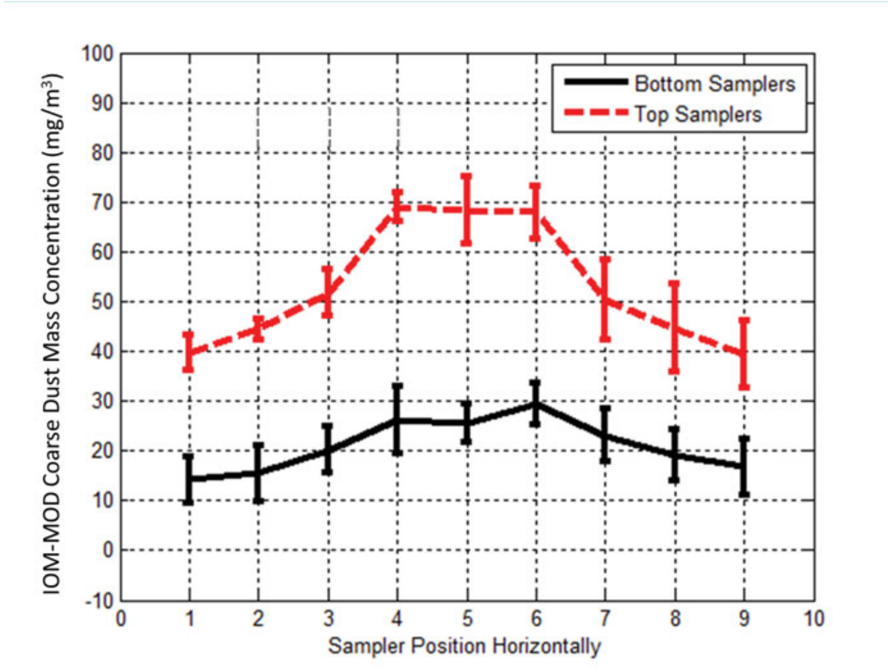

Figure 6. Spatial variation of coarse dust mass concentration across sampling rack as measured by array of IOM-MOD samplers shown in Figure 5 for 2.85 m/s free-stream air velocity. Four twenty-minute tests were conducted on four separate, nonconsecutive sampling days (72 total filters). The results were averaged for the bottom and top portions of the rack, with 95% confidence intervals given by the error bars.

ence between mean values was the least, and the coefficient of variation was reasonable at +/− 3.5% (Figure 6). This location allowed a comparison between samplers, as they were exposed to nearly the same concentration. It is important to develop relatively uniform and repeatable ambient dust concentrations in the laboratory to challenge dust samplers, since variable conditions exist in the field and add to experimental error. Studies in mines globally have shown that engineering controls which reduce airborne dust by up to 30% can be found to have contradictory results when retested elsewhere.[27] The spatial concentration variability was only measured at the more challenging condition of high airspeed and larger dust, as it is expected that with lower airspeed and smaller dust, lower concentration gradients would exist, resulting in more uniform dust dispersion.

Sampler comparison

The comparison of the four different samplers was performed within the (most) repeatable center zone with the lowest concentration gradient as described above. Based on this sampling location (top-center), the four sampler types were compared over the eight conditions given in Table 2, and a total of 32 filter samples were analyzed.

The masses collected by the IOM-MOD demonstrated the largest change in dust concentration with respect to air velocity of any sampler (Figure 7), as well as the lowest standard error across conditions (error bars in Figure 7). A large change in dust concentration was expected because dust feed rate was fixed while air velocity was increased about 5-fold. From low free-stream air velocity (low dilution) to high free-stream air velocity (high dilution), the IOM-MOD (with appropriate inlet nozzle) showed about a 3-fold decrease in concentration. However, the ZCD sampler showed much less change in dust concentration with increased dilution (Figure 7). As shown in Table 4, the mean coefficient of variation across tested conditions was 4.6, 6.5, 9.4, and 26.4% for the IOM-MOD, ZCD, ZCD-90, and IOM samplers, respectively. The IOM-MOD variability was 11-times less than the other sampler types (mean) at the condition that produced the most variability—low air velocity and coarse dust. Losses from deposition in the IOM-MOD inlet nozzle were estimated to be small relative to masses collected in the cassette. This is because previous testing with 127-mm-long stainless steel nozzles showed losses on the order of 5% using a washing/drying/weighing technique. Nozzles for the current study were shorter (38.1 mm), so it is reasonable to believe that losses in the inlet nozzles were less than 5%. The IOM-MOD inlet velocity was within 10% of the isokinetic sampling velocity, given tolerances in the nozzle inlet diameter (±0.15 mm) and control of the laboratory air velocity (± 0.01 m/s for low velocity and ± 0.05 m/s for high velocity).

As expected from isokinetic sampling theory,[12] the ZCD dust mass concentration was greater than the

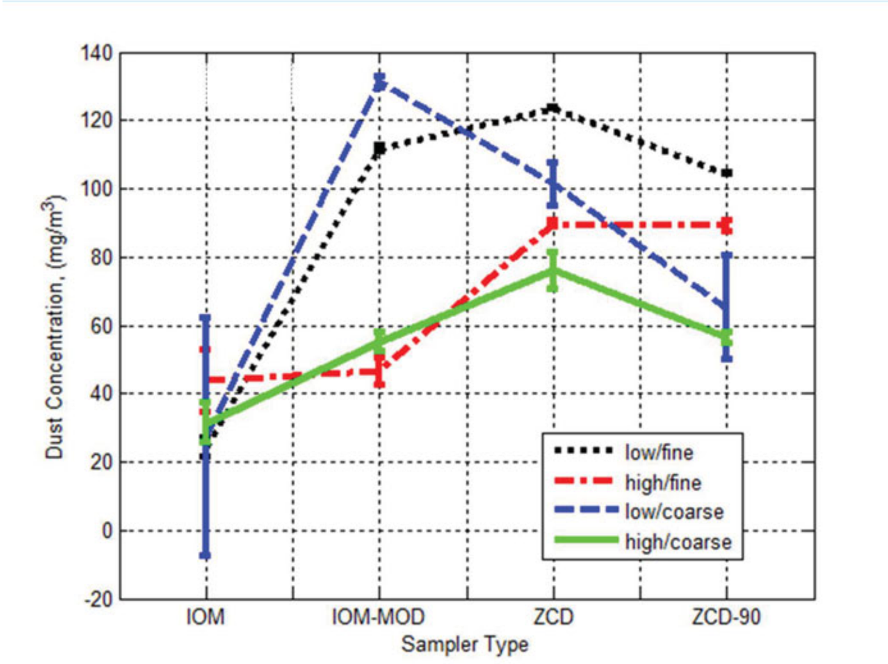

Figure 7. The average dust concentration and coefficient of variance (error bars) for two tests, each at the respective combinations of air velocity and dust size.

D concentration at low inlet to free-stream air velocity ratio, which corresponds to high free-stream air velocity 2.85 m/s (Figure 8). This effect was observed for both coarse and fine dust, and was not enhanced by coarse dust (Figure 8). The effect was not enhanced for coarse dust probably because the ZCD inlet is blunter than the IOM-MOD inlet. For a blunter inlet and turbulent air (7.6×10^5 Re in the current study), aspiration efficiency should be lower for larger particles, especially those above 40 µm;[13] this effect was shown relative to the IOM-MOD concentration in Figure 8. The ZCD mass concentration was 90% greater for fine and 40% greater for coarse dust relative to the IOM-MOD. The results suggest that the IOM-MOD made a significant difference when sampling for both fine and coarse dust in high-velocity ventilation air. Thus, for the most repeatable results, isokinetic sampling should be carried out in high-velocity mine ventilation air regardless of coal dust size distribution.

Consistent with isokinetic theory, for coarse dust the ZCD mass concentration was lower than the IOM-MOD concentration at high inlet to free-stream velocity ratio, which corresponds to low free-stream air velocity 0.5 m/s. The results were about 20% different, which may justify using the IOM-MOD at low air velocities for coarse dust, since the IOM-MOD coefficient of variation was only about 5%. For fine dust, the ZCD mass concentration was similar to the IOM-MOD—so for low air velocities, the ZCD may be an acceptable sampler if coarse dust masses do not need to be assessed.

Results for the IOM were inconsistent with isokinetic theory, since lower mass concentrations were collected relative to the IOM-MOD, although all conditions were sub-isokinetic. The authors believe the reason for this can be seen in Figure 3, in which the IOM inlet position was set back relative to the IOM-MOD inlet position. This suggests that the IOM inlet was exposed to more large-scale turbulence and irregular flow pattern effects from the sampling mounts and rack. In contrast, the IOM-MOD nozzle projected into the free-stream air (Figure 3) and was more likely to sample from undisturbed flow. The results for the IOM-MOD array (Figure 5) showed that in the repeatable center (described above) all IOM-MOD samplers collected comparable and repeatable dust mass concentrations. Since the IOM was placed

Table 4. Coefficient of variation (CV, %) for sampler comparison.

Sampler	Low Velocity Fine Dust	High Velocity Fine Dust	Low Velocity Coarse Dust	High Velocity Coarse Dust	Mean Results
IOM	5.8	18.2	69.8	11.8	26.4
IOM-MOD	1.8	7.8	3.4	5.4	4.6
ZCD	0.8	2.2	12.4	10.4	6.5
ZCD-90	0.4	3.4	30.4	3.4	9.4

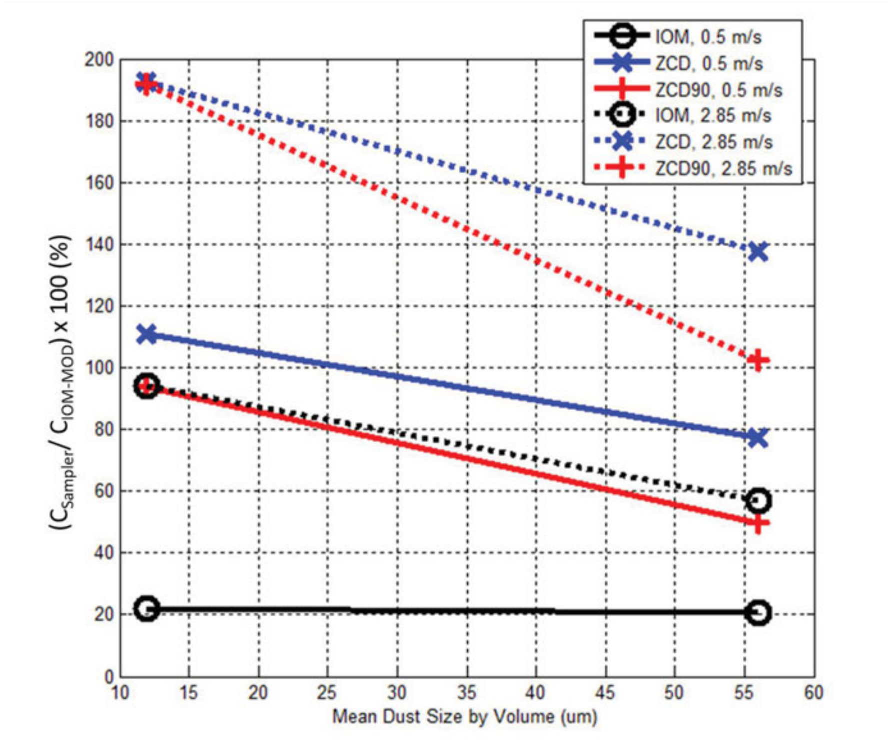

Figure 8. Ratio of a sampler's mean dust mass concentration ($C_{sampler}$) to that of the IOM-MOD ($C_{IOM\text{-}MOD}$) (given in percentage) for two bulk dust volume mean diameters.

within the comparable center zone, it should have been exposed to similar concentrations. However, because the inlet was not projected into the free-stream air, it was probably exposed to irregular flow patterns.

The ZCD inlet position was also set back relative to the IOM-MOD inlet position, and so the ZCD inlet could have been exposed to irregular flow patterns like the IOM. However, the ZCD inlet velocity was nine times greater than the IOM inlet velocity, so particles near the ZCD face were more likely to keep moving and enter the sampler while particles near the IOM inlet face experienced significant deceleration and were more likely to be influenced by irregular flow patterns. The coefficient of variance for each test condition, which is given by the error bars in Figure 7, shows that the ZCD mass concentrations were much more repeatable than those for the IOM. The repeatability of the ZCD mass concentration results and their consistency with isokinetic theory suggest that irregular flow patterns from the sampling rack and mounts did not greatly perturb relatively high-velocity flow at the ZCD inlet. Similarly, relative to the IOM, the ZCD-90 had high inlet velocity and repeatable mass concentrations. The coefficient of variation for the ZCD-90 was very low except for the condition of low air velocity and coarse dust (blue error bars in Figure 7). For the low free-stream air velocity and fine dust condition, the ZCD-90 mass concentration was similar to the IOM-MOD, possibly since the inlet to free-stream air velocity ratio was high and small particles may have followed flow stream lines into the sampler rather than bypassing it. Since these results are highly dependent on the given free-stream air velocity and particle size distribution, the similarity between the ZCD-90 and IOM-MOD may not be generalizable to various sampling conditions in underground coal mines. An analysis of the flow patterns around the sampling rack and mount would be needed to help understand why the ZCD-90 concentration at high free-stream air velocity was 90% greater than the IOM-MOD for fine dust and similar to the IOM-MOD for coarse dust. It would be expected that most particles would bypass the ZCD-90 at high air velocity without being sampled due to inertial effects, but because the cassette mount behind the inlet may have slowed the aerosol (Figure 3), particles may have been sampled more easily.

Conclusions

The side-by-side sampler comparison was made practicable by establishing that an area of relatively uniform mass concentrations existed in a particular area of the sampling space. Within this area, artifacts from ambient concentration gradients were minimal (coefficient of variation ±3.5%). The results were facilitated by aligning and securing the dust outlet, sampling rack and individual samplers.

The sampler comparison results suggested that there was a significant difference between the IOM-MOD and ZCD mass concentrations for the following conditions: (1) high air velocity (2.85 m/s) with fine dust (63% by volume < 10 μm), (2) high air velocity (2.85 m/s) with coarse dust (14% by volume < 10 μm), and (3) low air velocity (0.5 m/s) with coarse dust. For the condition of low air velocity with fine dust, the ZCD may be adequate, since the results were consistent with the IOM-MOD mass concentration. The study is limited to a relative comparison between samplers, since a well-controlled wind tunnel equipped with real-time aerosol sizers should be used to measure aspiration efficiency for each inlet as a function of dust diameter and air velocity.

The comparison of sampler repeatability demonstrated that only the IOM –MOD exhibited a CV less than 10% across all conditions. For the low airspeed and fine dust condition, all samplers had a low CV; however, for all other conditions (high airspeed/fine dust, high airspeed/coarse dust and low airspeed/coarse dust), the CV was greater than the requirement necessary to ensure adequate evaluation of engineering dust controls in the field. For sampler inlets that were not projected into the free-stream air (IOM and ZCD-90), irregular flow patterns and may have led to an increase in CV. For future studies, a probe (nozzle) should be added to sampler inlets to prevent particle collection from being disturbed by irregular flow patterns from the sampling rack and mounts.

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Disclaimer

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