Real-time Sizing of Airborne Coarse Coal Dust

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Airborne coarse coal dust mitigation may help reduce combustible material deposits on mine surfaces. Mitigating low-size-range coarse particles (e.g. sub-20 μm) is important because of their high flammability. However, larger particles also ignite at elevated concentrations and their removal efficiencies need to be assessed. Assessing this large size range may be possible using real-time cloud and aerosol spectrometer (CAS) light-scattering measurements. The measurement range depends on particle refractive index and morphology, and was evaluated for bituminous coal dust. The results suggested that CAS light-scattering measurements can be used to measure the conventional size range for combustible dust (≤ 74 μm).

Airborne coal dust mitigation serves as a supplementary strategy for meeting surface-dust incombustible content regulations.[1] Airborne dust is mitigated using control technologies which remove dust from the air course, preventing its deposition and accumulation on mine return airway surfaces. Technologies such as water sprays, flooded-bed wet scrubbers, and knockdown foaming agents have been evaluated for airborne dust removal efficiencies, and these results suggest that removal efficiencies differ for respirable (≤ 4 μm) and larger-size (coarse) dust.[2, 3] For such evaluations, removal efficiency measurements may be more challenging for coarse than respirable dust as discussed below.

Coarse dust is less responsive to changes in airflow streamlines from large-scale turbulence and is more influenced by initial release conditions and gravitational settling.[4, 5] As a result, coarse dust can be poorly distributed and have short airborne residence times. Due to these inhomogeneities, reduction efficiencies are more aptly assessed with real-time instruments that capture temporal and spatial variation in concentration. Such measurements are routinely made for sub-20 μm airborne particles using commercial aerodynamic particle sizers.[6] However, methods for larger particles are often specialized because of sampling and analysis challenges.[7-9]

A possible solution for this problem is the cloud and aerosol spectrometer (CAS; DMT, Boulder, CO), which can measure, in real-time, the size distributions of a wide range of coarse particles. The CAS was specialized for atmospheric aerosol studies by configuring the instrument for passive sampling from aircraft and for generating real-time size distributions of water droplets 0.5 μm – 50 μm.[10] Although the CAS was specialized for *in situ* atmospheric studies, it can be adapted for laboratory investigations by installing a pump to the instrument outlet, thus creating an active sampling regime.[11] In addition, CAS single-particle light-scattering measurements can be modeled to generate real-time size distributions for the particles of interest.[12]

Previously, the CAS has been used to characterize ash clouds emitted by volcanic eruption using a light-scattering theory for irregular particles—ray tracing with diffraction on facets (RTDF).[12, 13] RTDF theory differs from classical geometric optics by considering diffraction at facets in addition to diffraction at the projected cross section and therefore describes the size-dependence better. Fractal-like irregular shapes were used since they are a more realistic representation of ash than the smooth, compact and symmetrical geometry of spheres or spheroids. The results for volcanic ash were not exceedingly different from CAS optical size distributions for water droplets. This is due to the cancellation between opposing effects of increased particle cross-sectional area per unit volume for the irregular particles compared to spheres (leading to a higher diffraction contribution on the detector), versus slightly increased absorption, and a decreased preference for forward scattering for the volcanic ash compared to water due to the different refractive indices (leading to a decrease of refracted contributions on the detector). However, for strongly absorbing materials such as coal dust, particle size distribution estimates should differ substantially from water droplet size distribution estimates.

In the current study, CAS sizing of bituminous coal dust was studied through RTDF computations of forward light-scattering intensities for irregular particles. The CAS measurement range should be extended beyond that for water (50 μm), because larger diameter coal dust would be required to produce light-scattering intensities great enough to saturate the detection system. Sizing of coal dust in the conventional range for combustible dust (≤ 74 μm) was studied by first calibrating the CAS with glass sphere standards, and subsequently comparing size distribution results for RTDF modeling of CAS measurements (CAS/RTDF) and a conventional laser diffraction particle sizer by Beckman Coulter (Brea, CA).

Methods

The CAS measures single-particle forward light-scattering intensity (integrated over an angular range of 4˚ to 12˚ with respect to the incidence direction), which is proportional to particle optical scattering cross section. The optical scattering cross section is modeled to estimate particle diameter using information on particle refractive index and morphology. The classical model for spheres is Mie theory [14, 15] and is employed by CAS software to estimate the diameter of water droplets with an index of refraction of 1.33. To improve estimates for light-absorbing and irregularly shaped coal dust, RTDF theory was used to determine volume equivalent diameters.

Materials

The CAS was calibrated using coarse-size-range glass sphere standards. The standards were NIST traceable glass spheres from SPI Supplies (5.4 ± 0.7 μm, 10.0 ± 1.1 μm, 15.9 ± 1.6 μm, and 18.2 ± 1.8 μm borosilicate with index of refraction 1.56), Whitehouse Scientific (31.33 ± 0.82 μm soda-lime with index of refraction 1.52), and Duke Scientific Corp. (52.6 ± 3.2 μm soda-lime with index of refraction 1.52).

Coal dust particle size distributions were estimated through CAS/RTDF measurements on a bituminous coal with low volatile content, Pocahontas No. 3. This coal type was selected for this study to allow the study results to be employed in the authors' investigations of mitigation strategies involving water sprays. Its hydrophobicity presents a challenge to water spray removal and would allow a conservative removal estimate. The index of refraction of Pocahontas No. 3 coal was measured previously by a reflectance method (1.85–0.23i) [16] and the reference was suggested in a review of light-absorption by carbonaceous particles.[17] The chosen refractive index value is an approximation for the current study because it was measured at wavelength 650 nm, while the CAS measurement is at 658 nm.

The Pocahontas coal was pulverized by Hadsell Chemical LLC (Hadsell) to produce a volume-size distribution within the conventional range for combustible dust (≤ 74 μm).[18] The size distribution provided by Hadsell was measured by a laser diffraction particle size analyzer (LS 13 320, Beckman Coulter, Brea, CA) with data analysis software that employed the Fraunhofer model (Beckman). The Beckman size distribution was compared with CAS measurements for both total dust and for a 32 μm–45μm dust, selected by air-jet sieving (Micron Air-Jet Sieve, Hosokawa Micron Powder Systems, Summit, NJ).

Calibration and Coal Dust Analysis

The glass sphere standards and coal dust were delivered to the CAS following de-agglomeration by a small-scale powder disperser (SSPD; TSI Inc., model 3433). [19] The SSPD was operated with 2 L/min capillary flow, which vacuumed dust from a turntable platform; and with 28 L/min sheath flow, which de-agglomerated particles in the Venturi aspirator. Aerosol exiting the SSPD was introduced to the CAS along with high flow rate (1.5×10^4 L/min) HEPA-filtered air to avoid coarse particle settling and background particle interference. The CAS and SSPD were aligned vertically to prevent particle gravitational settling along the flow path (Figure 1).

Single particles passing through a 120 μm beam width were detected and processed. The CAS forward light-scattering detector (4º–12º) gave a voltage signal, which was sampled by an analog-to-digital (A/D) converter; and the final output given was in terms of counts. The counts value for a single particle is proportional to forward light-scattering intensity, which in turn is proportional to the optical scattering cross section. The compound proportionality constant between counts and optical scattering cross section was measured for this calibration. For each glass sphere standard, the most frequent counts value was divided by the scattering cross section from Mie theory to determine the proportionality constant. This was done for multiple glass sphere standards, and the average proportionality constant was determined. The counts value for each coal dust particle was divided by this proportionality constant to determine an optical scattering cross section.

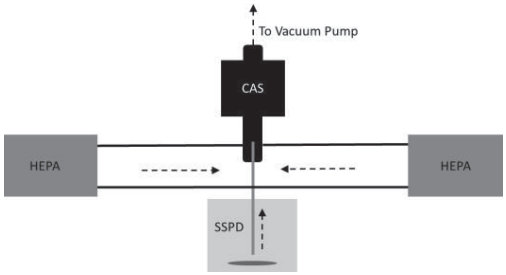

Figure 1: Diagram of how coal dust or glass spheres were dispersed by the SSPD and delivered to the CAS

Light-Scattering Model for Coal Dust

The coal dust optical scattering cross section was modeled by RTDF theory [13] to estimate volume equivalent diameter. RTDF theory includes light diffraction by (1) the particle projected cross section and (2) surface facets; both are characteristics of dust morphology. The faceted morphology approximation was based on a distorted triadic Koch fractal described in Macke et al. [20] (Figure 2a). Random tilt of facets was assumed, because it provided an effective smoothing of the surface as well as a randomization of overall particle shape. Figure 2b shows a representative particle of the coal dust used in the current study obtained by qualitative scanning electron microscopy (SEM) analysis.

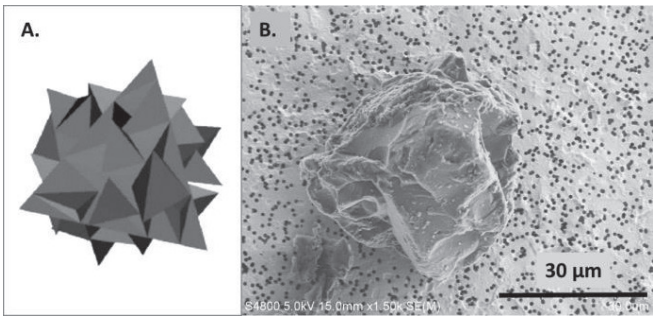

Figure 2: A) Distorted fractal-like crystal. This crystal shape was randomized to model an irregular particle with rough surface. B) Pocahontas coal dust with smoother surface

Through computer-controlled SEM analysis, projected properties were measured, and, on average, the coarse dust was elongated with an aspect ratio of 1.36 ± 0.18. Elongated particles were assumed to be randomly oriented since the flow was highly turbulent (velocity 25 m/s and Reynolds number 5×10^4 in the CAS).[21] Further discussion of the measurement methods and resulting differences in volume equivalent diameter will be submitted for future publication due to the unique sampling and analysis procedures.

The above approximations were used in determining coal dust size distributions for particles larger than 1.5 µm. Smaller particles were modeled by T-matrix theory, for which dust morphology was represented as hexagonal cylinders.[22] T-matrix computations enabled reporting comprehensive size distributions, but the following discussion section is focused on the RTDF results for larger dust. Three-dimensional morphology measurements were not made because of project time constraints but may be considered for future work. This could be important because large dust may "lie flat" on a surface, concealing a relatively small height in comparison to projected diameter.[23]

Results and Discussion

To calibrate the CAS, several glass sphere standards were analyzed following de-agglomeration by the SSPD (Figure 1). Narrow ranges of A/D counts were measured for the 5 µm and 20 µm (nominal) standards and the distribution of each was well-defined (Figure 3). For these standards, the proportionality constant between A/D counts and optical scattering cross section was determined by locating the manufacturer-specified diameter on the Mie curve to estimate optical scattering cross section. Unfortunately, both standards were located on a steep portion

of the Mie curve, in which a small change in diameter corresponded to a relatively large change in scattering cross-section (Figure 3). However, the error from this potential change was relatively small in comparison to the difference between the proportionality constants for the nominal 5 µm (26.8) and 20 µm (33.6) standards. Rather than averaging these two proportionality constants, a better estimate could be obtained by averaging the results for several glass sphere standards. This averaging was attempted, but a prominent peak from small particle artifacts in the glass sphere standards obscured the distributions (Figure 4). This peak was especially problematic for the 10 µm and 15 µm standards. The coarse 'nominal' particle peak appeared as a "shoulder" of the small particle peak artifact (Figure 4). Furthermore, the broad distribution for the 31 µm glass sphere standard led to an ambiguous peak (Figure 4, bottom row), and would not improve the accuracy of the calibration.

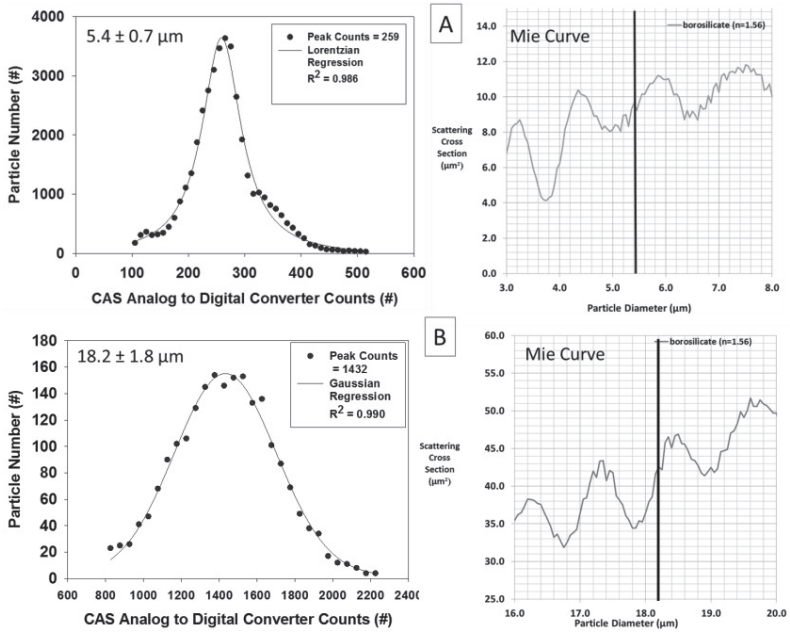

Figure 3: A/D count distribution and Mie curve position for the nominal 5 µm and 20 µm glass sphere standards

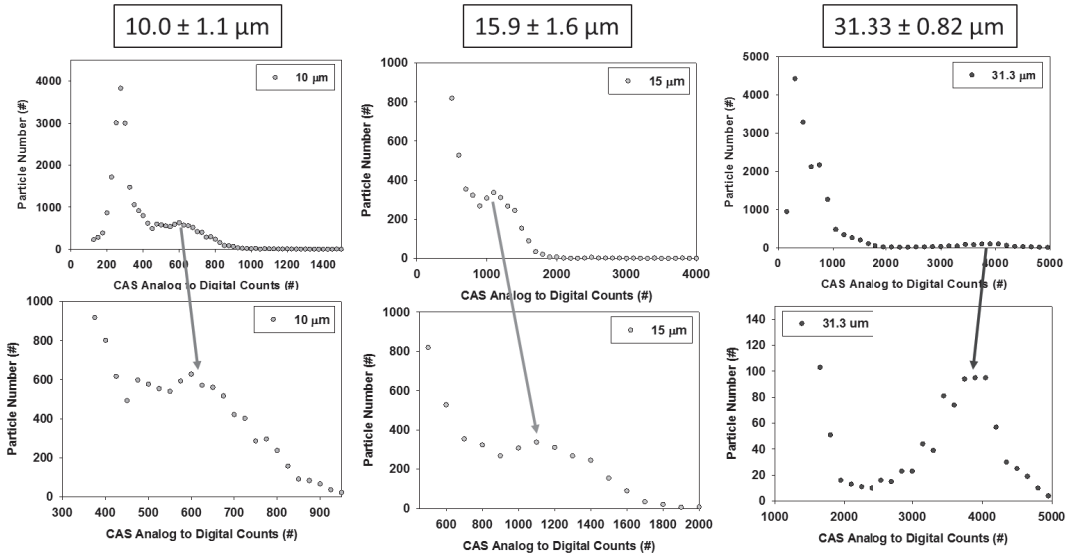

Figure 4: The entire distribution (top row) and the subset (bottom row) containing the indicated size (boxed)

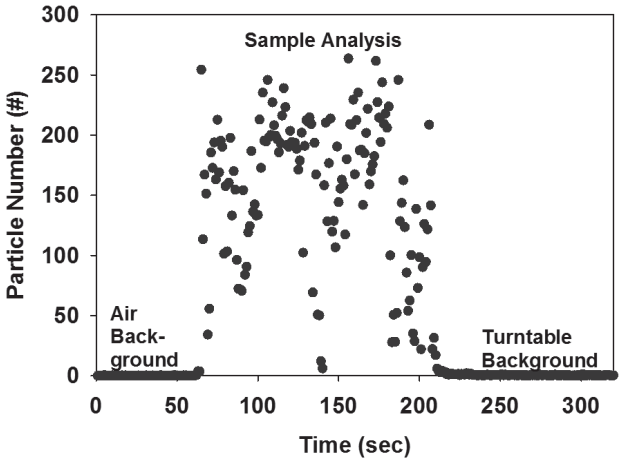

Figure 5: CAS-measured particle number in background air, during sample analysis, and from the disperser turntable

Given the relatively large artifact peaks (Figure 4, top row), it is reasonable to suspect that small particles were present in the background aerosol or on the disperser turntable rather than in the certified standards. However, the number of particles in the background air and those dispersed from the turntable were negligible as shown in Figure 5. Thus, only the 5 µm and 20 µm data were used to determine the average proportionality constant, which was 30.2. This process is usually implicit in studies utilizing the CAS [12, 24]; however, because the results were unexpected and were influential in the final coal dust sizing results, they are detailed in the current work.

Based on the above calibration, single-particle optical scattering cross sections were estimated for coal dust; and the corresponding volume equivalent diameters were computed using RTDF theory. The resulting size distributions were compared with the Beckman size distribution provided by Hadsell. The comparison was made by consolidating the CAS data to 2D Graph 1 at the CAS peak diameter (9

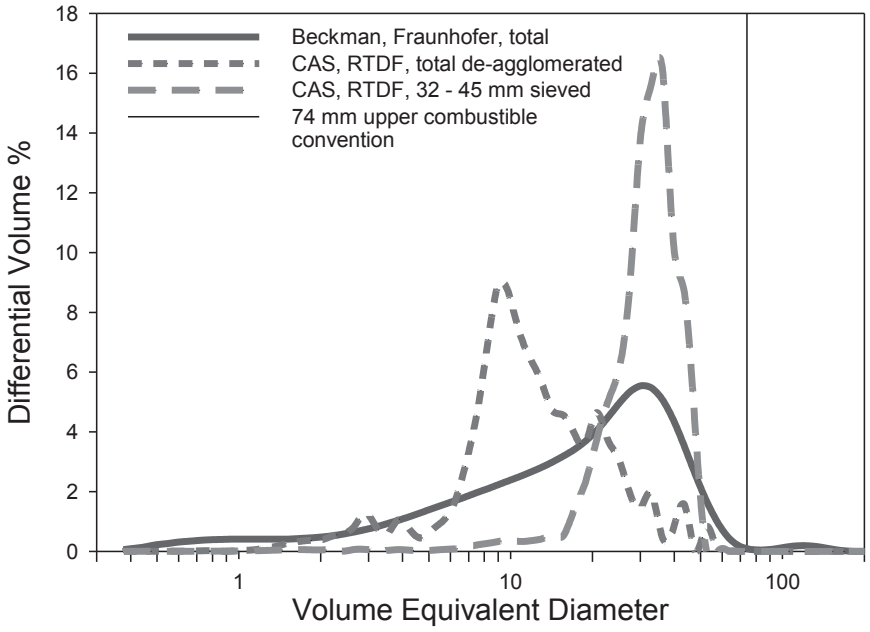

Figure 6: Coal dust volume-size distributions by RTDF modeling of CAS measurements and by a conventional laser diffraction particle sizer

Although different analytical techniques and models were used, most of the discrepancy probably resulted from the different sample dispersion methods. For analysis by the CAS, bulk coal dust was thoroughly de-agglomerated by the SSPD. In contrast, the Beckman inlet disperser probably had a limited effect on agglomerate break-up. To test this hypothesis, the bulk coal dust was sieved to collect a sample of coal dust consisting of particles between the sizes of 32 μm and 45 μm—a task that required months of air-jet sieving. Because almost all of the bulk dust passed through the 32 μm sieve, the sieving procedure had to be repeated excessively to amass enough sample to complete this comparison. Once sufficient samples in the size range between 32 μm and 45 μm were collected, the samples were introduced to the CAS, and the diameter estimates by RTDF theory were found to be consistent with the sieved size range (Figure 6; long dash curve). This supports the accuracy of the CAS measurements with RTDF estimates, although the resul

2D Graph 1

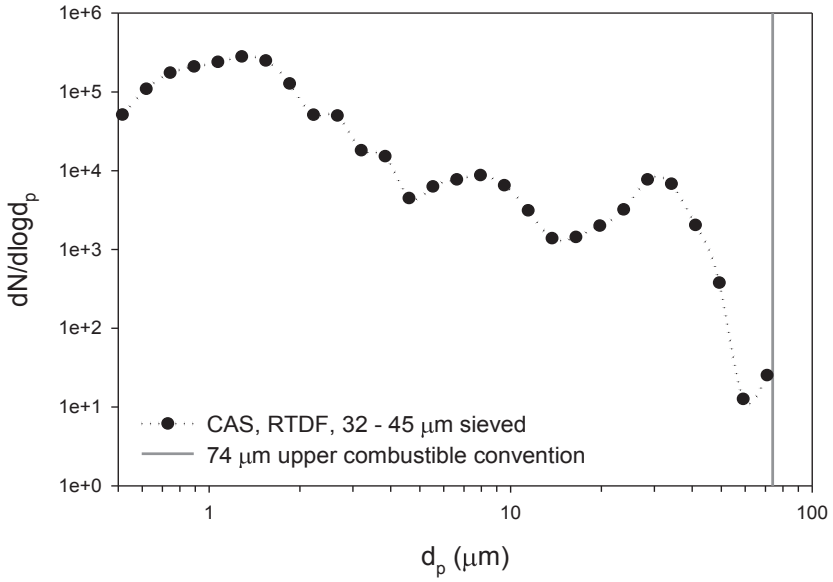

Figure 7: Number-size distribution of sieved dust 32 μm–45 μm by RTDF modeling of CAS measurements

As suggested above, the bulk dust was composed of smaller particles than indicated by the Beckman size distribution. As a result, the bulk dust contained few particles in the range of 32 μm–45 μm, and those larger were even less abundant. Thus, with low occurrence of 50 μm–75 μm particles in the total dust it was difficult to demonstrate that the measurement range of the CAS extended to the upper size range for combustible dust (74 μm). However, evidence for this appeared in the sieved dust number-size distribution, as described in what follows. The size distribution for 32 μm–45 μm sieved coal dust was plotted on a number basis (Figure 7) rather than the volume basis as in Figure 6. The comparison between Figures 6 and 7 shows that sub-20 μm particles were numerous but were not major contributors to the volume-size distribution. These particles were probably attached to larger dust and could not be stripped by the air-jet sieve, which was used to select the 32 μm-45 μm size range. This can be expected since the relatively high-rank coal is especially difficult to de-agglomerate because of its electrostatic properties.[25] In addition to sub-20 μm dust, particles larger than the sieve size range (32 μm–45 μm) were present. This is because size ranges selected through sieving are not sharp cut-offs, but instead are log-normal distributions that include particles with diameters beyond the sieve screen value.[26]

As indicated by Figure 7, sieved dust 32 μm–45 μm included particles with diameters near the upper boundary of the combustible dust convention value (74 μm). These large particles should be detected by the CAS based on the tolerances of the optics and signal processing systems. The optics limit for size detection depends on the beam width through which a particle must pass and scatter light (120 μm). The limit due to signal processing is based on the saturation of the A/D converter and corresponds to the light-scattering intensity of a 50 μm water droplet. Since coal dust 74 μm in diameter fits within the beam width and scatters light with intensities of a 28 μm water droplet, these limits should not impede detection of the upper size range for combustible dust.

Although very few 50 µm – 75 µm were present in the total dust, individual particles were detected in concurrent studies carried out in an experimental mine gallery.[27] Total dust was sized through CAS/RTDF measurements, and individual particles 50 µm–75 µm appeared in 6 of 90 tests, in which they represented 1 of 10^3–10^4 particles. Since few of these particles were present in the bulk dust and some settled between the dust disperser and CAS system (12 meters; 3.6 m/s air velocity), the low occurrence is expected. These results, along with the wide-range size distribution given in Figure 7, show examples of CAS/RTDF measurements covering the conventional size range for combustible dust. Accuracy for large-size-range coarse coal dust is supported by the consistency between CAS/RTDF estimates and the sieved dust size range (Figure 6).

Conclusions

The CAS study results suggest that coal dust size distributions can be measured in real-time over the conventional size range for combustible dust using RTDF light-scattering theory for irregular particles. Coal dust size distributions estimated by RTDF theory agreed with the test dust size range and covered the conventional size range for combustible dust. Measurement of the total size distribution in an experimental mine gallery showed the intermittent presence of 50 µm-75µm particles. The total dust size distribution peaked at smaller sizes relative to laser diffraction particle sizer measurements. This may have occurred because coal dust samples were more thoroughly de-agglomerated by the dust disperser used for CAS measurements than by the inlet disperser of the laser diffraction particle sizer.

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