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Examination of a newly developed mobile dry scrubber (DS) for coal mine dust control applications

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Abstract

The Office of Mine Safety and Health Research of the U.S. National Institute for Occupational Safety and Health (NIOSH OMSHR) conducted laboratory testing of a self-tramming, remotely controlled mobile Dry Scrubber (DS) that J.H. Fletcher and Co. developed under a contract with NIOSH OMSHR to reduce the exposure of miners to airborne dust. The scrubber was found to average greater than 95 percent dust removal efficiency with disposable filters, and 88 and 90 percent, respectively, with optional washable filters in their prewash and post-wash test conditions. Although the washable filters can be reused, washing them generated personal and downstream respirable dust concentrations of 1.2 and 8.3 mg/m^3, respectively, for a 10-min washing period. The scrubber's velocity-pressure-regulated variable-frequency-drive fan maintained relatively consistent airflow near the targeted 1.42 and 4.25 m^3/s (3,000 and 9,000 ft^3/min) airflow rates during most of the laboratory dust testing until reaching its maximum 60-Hz fan motor frequency or horsepower rating at 2,610 Pa (10.5 in. w.g.) of filter differential pressure and 3.97 m^3/s (8,420 ft^3/min) of scrubber airflow quantity. Laboratory sound level measurements of the scrubber showed that the outlet side of the scrubber was noisier, and the loaded filters increased sound levels compared with clean filters at the same airflow quantities. With loaded filters, the scrubber reached a 90 dB(A) sound level at 2.83 m^3/s (6,000 ft^3/min) of scrubber airflow, indicating that miners should not be overexposed in relation to MSHA's permissible exposure level — under Title 30 Code of Federal Regulations Part 62.101— of 90 dB(A) at or below this airflow quantity. The scrubber's washable filters were not used during field-testing because of their lower respirable dust removal efficiency and the airborne dust generated by filter washing. Field-testing the

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scrubber with disposable filters at two underground coal mine sections showed that it could clean a portion of the section return air and provide dust reduction of about 50 percent at the face area downstream of the continuous-miner operation.

Keywords

Coal mining; Respirable dust; Dust collector; Scrubber

Introduction

Coal mine worker overexposure to coal and quartz dust continues to be a problem at underground coal mining operations in the United States. The U.S. Mine Safety and Health Administration (MSHA) recently changed the standard for coal mine worker respirable dust exposure from an average of 2.0 mg/m^3 during an eight-hour shift to an average of 1.5 mg/m^3 over the actual working shift, effective as of Aug. 1, 2016, under Title 30 Code of Federal Regulations Part 70.100. Furthermore, under 30 CFR Part 70.101, if more than 0.1 mg/m^3 quartz mass is found in the coal mine worker dust sample, the applicable respirable dust standard is further reduced to the quotient of 10 divided by the percentage of the quartz in the sample (MSHA, 2015a). More than 90 percent of the mechanized mining units operating in U.S. underground coal mines are continuous mining machines (MSHA, 2015b). MSHA inspector dust samples from 2009 to 2012 showed that 3.7 percent of continuous-miner operators exceeded the 2.0 mg/m^3 dust standard. Of these dust samples, 8.8 percent exceeded the new 1.5 mg/m^3 dust standard and 9.7 percent exceeded the reduced quartz standard (U.S. Department of Labor, 2013). Additionally, roof bolter dust samples at these mechanized mining units during this same period have exceeded the 2.0 mg/m^3, 1.5 mg/m^3 and reduced quartz levels at 1.1, 3.7 and 10.6 percent, respectively (U.S. Department of Labor, 2013).

On-board flooded-bed scrubbers on continuous mining machines are proven, efficient collectors of respirable dust (Fields, Atchison and Haney, 1990; Colinet and Jankowski, 1996; Potts, Reed and Colinet, 2011; Colinet, Reed and Potts, 2013). However, dust bypassing the scrubber may expose roof bolter operators who work downwind of the continuous miner to high levels of respirable dust (Colinet, Reed and Potts, 2013). Respirable dust concentrations downwind of the continuous miner can greatly exceed regulatory standards and overexpose roof bolter operators, especially when the continuous miner does not employ a flooded-bed scrubber (Colinet, Reed and Potts, 2013). To combat the upstream continuous-miner dust source, a portable standalone scrubber can be strategically placed to clean the dust-laden air before it enters the roof bolter workplace entry, providing the bolter operators with a cleaner air supply and thereby reducing their dust exposures.

J.H. Fletcher and Co. (Huntington, WV) developed a self-tramming, standalone Dry Scrubber, referred to as DS or simply as scrubber in this report, under a contract with the Office of Mine Safety and Health Research of the U.S. National Institute for Occupational Safety and Health (NIOSH OMSHR), called NIOSH Contract No. 200-2010-36164, “The

Development of Dust Control Units for Underground Coal Mines" (Kendall, 2015). The prototype scrubber (Fig. 1) was delivered to NIOSH OMSHR for operational and dust collection efficiency testing. The general specifications of the prototype are:

- Machine dimensions: 1.22 m wide × 1.22 m high × 4.79 m long (4 ft wide × 4 ft high × 15.7 ft long).
- Air mover: 22.4 kW (30 hp) vane axial fan (480 V) with variable frequency drive speed controller.
- Filtration: Dual 71-cm (28-in.) outer diameter (O.D.) cylindrical air filters rated at 99 percent efficiency for 2-μm particles.
- Tram system: Crawler tram hydraulically controlled by remote transceiver.
- Hydraulic system: Remote transceiver controlled, 12-V pilot solenoid function operation, variable flow axial piston pump with designated 30-hp electric motor (480 V).

Laboratory testing was initially conducted at NIOSH OMSHR to examine the scrubber's respirable dust collection efficiency and its operational performance with disposable or washable filter cartridges. Functional and operational modifications were made during and after the laboratory testing to prepare the scrubber for further underground field-testing. Field-testing was conducted at two sections in an underground mine to examine its effectiveness in reducing dust levels at the face area downstream of the continuous mining machine. This report describes the results from both the laboratory testing and field-testing of the scrubber.

Laboratory testing

The Fletcher Dry Scrubber was tested for operational performance and dust collection efficiency in the continuous miner gallery at NIOSH OMSHR's laboratory in Pittsburgh, PA. The testing was conducted in the intake entry of the continuous miner dust gallery (Fig. 2). Airflow measurements were initially taken of the scrubber to validate its fan-controlled variable frequency drive (VFD) response to its internal pitot tube velocity pressure measurement. Several modifications were initially made by Fletcher to the velocity pressure transducer and the VFD fan controller to improve agreement with the preset dry scrubber airflow quantity and the amount delivered as the filter loaded with dust. After the scrubber's airflow controller response was improved, dust removal efficiency and filter loading tests were performed with the disposable filter cartridges and the alternative washable, reusable filter cartridges.

Airflow measurements

Eight air velocity sampling holes were drilled 7.6 cm (3 in.) downstream of the fan discharge transition point along the top cross section of the discharge duct, which is 122 cm wide and 31 cm high (48 in. wide and 12 in. high). This provided a stationary 32-point equal area air velocity sampling grid at four measurement heights and eight horizontal locations across the duct for determining the average air velocity and air flow quantity of the dry scrubber. The dry scrubber's fan had a VFD controller that was regulated by a pitot tube velocity pressure transducer measurement at the center of the discharge duct. A TSI Model 8346 Veloci-CALC hot wire anemometer (TSI Inc., Shoreview, MN) was used to measure the air velocities across the sampling grid, which were averaged and multiplied by the 0.372-m^2 (4-ft^2) duct area to determine the air quantity of the dry scrubber at planned dust testing quantities of 1.42 and 4.25 m^3/s (3,000 and 9,000 ft^3/min). A one-minute moving traverse was also made across the scrubber's 0.372-m^2 (4-ft^2) discharge area before and after the hot wire measurements with a high-speed vane anemometer (Davis Instrumentation Mfg. Co., Baltimore, MD) mounted on a 121.9-cm (4-ft) extension wand to measure its average air velocity and quantity at the preset airflows. Finally, a Series 166T telescoping stainless steel pitot tube with a 0- to 1.0-in. water gage magnehelic differential pressure gage (Dwyer Instruments, Michigan City, IN) was used to measure the velocity pressures and average air velocity across the sampling grid in conjunction with additional vane anemometer measurements at the scrubber discharge. These pitot tube measurements were also used to identify several stable velocity pressure monitoring grid locations for continuous monitoring of the dry scrubber airflow during NIOSH's tests for dust removal efficiency and filter loading.

Dust testing procedures

Dust efficiency testing was conducted on the scrubber at low and high airflow quantities of 1.42 and 4.25 m^3/s (3,000 and 9,000 ft^3/min). The targeted airflow of 1.42 m^3/s (3,000 ft^3/min) is the minimum ventilation airflow quantity allowed to a working coal face where coal is being cut, mined, drilled for blasting or loaded, under 30 CFR Part 75.325 (MSHA, 2015a). The targeted airflow of 4.25 m^3/s (9,000 ft^3/min) is the minimum ventilation airflow quantity allowed at the last open crosscut of each set of entries or rooms, under 30 CFR Part 75.325 (MSHA, 2015a), which is the planned operating location for the dry scrubber to clean a portion of the airflow for the roof bolting machine when operating downstream of the continuous miners.

During laboratory dust testing, the velocity pressure inside the exhaust duct and the differential pressure across the filters were continuously monitored and recorded for the dust efficiency testing. The negative differential pressure across the filters was measured with either a 0- to 2,490-Pa (0- to 10-in. w.g.) or a 0- to 4,980-Pa (0- to 20-in. w.g.) magnehelic pressure instrument with a 4- to 20-mA output (Dwyer Instruments Inc., Michigan City, IN) connected with Tygon tubing to a copper tube inserted inside the filter cartridges between the gasket seals. The velocity pressure was measured with a 0- to 249-Pa (0- to 1-in. w.g.) magnehelic pressure instrument with a 4- to 20-mA output (Dwyer Instruments Inc., Michigan City, IN) connected to a Dwyer Series 166T telescoping stainless steel pitot tube inserted into the exhaust duct. The pitot tube was initially inserted at grid location 12, where its velocity measurement was close to the grid average, and later placed at a higher air velocity location of 14 during most of the dust testing to increase the velocity pressure resolution at the lower scrubber quantity of 1.42 m^3/s (3,000 ft^3/min). These instruments were electronically recorded by a Telog R-3307 seven-channel data acquisition system (Telog Instruments, Inc Victor, NY).

Coal dust was introduced at the entrance of the intake entry of the continuous miner gallery, as shown in Fig. 2. The coal dust used was Pulverized Keystone Mineral Black 325BA (Keystone Filler & Manufacturing Co., Muncy, PA), which is −325 mesh (−44 μm) Pocahontas No. 3 coal dust, with 45 percent of this dust less than 10 μm in size. This pulverized coal dust was fed into the gallery through a screw feeder (Vibra Screw Inc., Totowa, NJ) and two LH-1/2 brass eductors (Penberthy, Prophetstown, IL) operating between 4 and 6 psig of compressed air. The eductors aerosolized and discharged the dust through two hoses at mid-entry height located 1/3 of the entry width away from the left and right sides of the entry. The dust cloud was drawn down the entry by the scrubber operating at air quantities of 1.42 and 4.25 m^3/s (3,000 and 9,000 ft^3/min). A sealed curtain wall with a door was constructed around the scrubber to separate the inlet and outlet ends of the scrubber, thereby isolating the upstream (dirty) and downstream (cleaner) airstreams inside the gallery (Fig. 2). An entrance door near the continuous miner gallery face area was left open during testing so that the pressure differential across the temporary wall around the scrubber would remain neutral when operating both the scrubber and gallery fan. The gallery's ventilation airflow quantity was set at approximately 0.47 m^3/s (1,000 ft^3/min) higher than the targeted scrubber airflow quantity by adjusting the regulator doors in the shared return air course between NIOSH's long-wall and continuous miner galleries (Fig. 2). Airflow quantity of the gallery was determined and adjusted by measuring the average velocity across the 1.8-m^2 (18.9-ft^2) entrance area of the continuous miner gallery return with a vane anemometer (one-minute moving traverse), before the operation of the scrubber. After the gallery airflow quantity was preset for the test, the scrubber airflow was preset to the desired airflow quantity and measured with a vane anemometer traverse of the scrubber discharge before and after each test. All dust efficiency testing was conducted with the straight exhaust configuration. An optional 90° angled discharge duct is available to redirect the exhaust air to either side of the scrubber but was not used during the laboratory dust testing.

Respirable concentrations were measured at two locations downstream and upstream of the dry scrubber, as shown in Fig. 2. Location numbers 1 and 2 were positioned 3.05 m (10 ft) downstream of the scrubber exhaust at mid-entry height and 1/3 of the entry width away from the left and right side walls of the entry. Location numbers 3 and 4 were positioned 3.05 m (10 ft) upstream of the scrubber inlet at mid-entry height and 1/3 of the entry width away from the left and right side walls of the entry. Gravimetric respirable dust concentrations were measured with coal mine dust personal sampling units (CMDPSU), consisting of an ESCORT-Elf constant flow air sampling pump pulling dust-laden air at 2.0 L/min through a 10-mm nylon cyclone (respirable dust classifier) and depositing the respirable fraction onto a pre-weighed 37-mm filter cassette (Zefon International, Ocala, FL). A pair of CMDPSUs and one real-time personal DataRAM pDR model 1000 instrument (Thermo Fisher Scientific, Waltham, MA) were placed and operated at each of the four sampling locations during each test. The average of the gravimetric dust concentrations measured downstream (from locations 1 and 2) and upstream (from locations 3 and 4) of the dry scrubber were used to determine the dry scrubber respirable dust removal efficiency for each test. Respirable gravimetric concentrations used in this analysis were not adjusted to MSHA's MRE compliance sample equivalents (multiplied by 1.38).

Dry scrubber dust testing was performed with a set of disposable and washable filter cartridges. The washable filters were also tested in their prewash and post-wash conditions. Each set of scrubber filters were successively tested during four one-hour test replicates at two scrubber preset airflows of 1.42 and 4.25 m^3/s (3,000 and 9,000 ft^3/min). After completion of the one-hour tests, the filters were further evaluated during two-hour tests at the scrubber preset airflow of 4.25 m^3/s (9,000 ft^3/min) to observe for diminished scrubber performance from additional filter dust loading. The number of additional two-hour tests performed on the disposable, prewash and post-wash filters were two, three and one, respectively. The dust concentrations generated for these tests varied somewhat between the different airflow tests but averaged 17.8 ± 3.3 mg/m^3, 17.4 ± 3.7 mg/m^3 and 19.1 ± 3.9 mg/m^3 (at the 95 percent confidence level), respectively, for the disposable, prewash and post-wash filter tests. After the prewash filter tests were completed, the filters were removed from the scrubber and back-flushed from the inside of the filter cartridge with a standard garden hose and twist nozzle until the water running off the filters was relatively clear. A real-time personal DataRam pDR model 1000 instrument was worn by the person washing the filter and another pDR was placed 3.05 m (10 ft) downstream in the gallery from where the filters were washed over a 10-min. period. These pDR dust concentrations were adjusted or calibrated to the CMDPSU's gravimetric concentrations measured during these laboratory tests. The post-wash filters were set out and air-dried for about 24 h, when the filter media was damp to the touch, and run for about another hour in the scrubber at 1.42 m^3/s (3,000 ft^3/min) to completely dry them out before the post-wash filter dust testing.

Sound level measurements

Sound level measurements were also taken on the dry scrubber operating inside the dust gallery with unloaded disposable filters before dust testing and with loaded washable filters at the completion of dust testing. A tripod-mounted Larson Davis LxT sound level meter (PCB Piezotronics Inc., Depew, NY) was used to measure the equivalent continuous sound level 3.05 m (10 ft) from the inlet side of the scrubber and 3.05 m (10 ft) from the outlet side of the scrubber at a height of 1.5 m (59 in.) with the microphone pointing at the scrubber. The measurement locations were approximately centered on the width of the scrubber. Initial sound level measurements were made at three scrubber airflow settings with the unloaded disposable filters (clean filters) before dust testing began. A second set of sound level measurements were taken for eight scrubber airflow settings with the loaded washable filters (loaded filters) after completion of all dust testing. A vane anemometer was swept across the discharge of the scrubber to determine the airflow at each scrubber operating point. For each airflow setting, three 15-second-long sound level measurements were taken and the logarithmic average of the three sound level measurements was calculated using the following equation:

$$\overline{L_{Aeq}}=10\log\left(1/3\left(10^{L_{Aeq,1}/10}+10^{L_{Aeq,2}/10}+10^{L_{Aeq,3}/10}\right)\right) \quad (1)$$

Laboratory test results

Table 1 shows the airflow quantities measured with the hot wire, pitot tube and vane anemometers, compared with the preset scrubber airflows of 1.42 and 4.25 m^3/s (3,000 and 9,000 ft^3/min). This table shows that there was initial disagreement between the lower dry scrubber airflow target and the measured airflow quantities. After Fletcher visited OMSHR's laboratory and made velocity pressure transducer and VFD fan controller modifications, better agreement was achieved between the preset dry scrubber airflow quantity and airflow measurements. Once the scrubber's airflow controller response was improved, dust removal efficiency and filter loading tests were performed with the disposable filter cartridges and the washable filter cartridges.

Figures 3 and 4 show the scrubber's dust collection efficiency results and average scrubber airflow measurements (vane anemometer) for the tests with the disposable filter cartridges and the washable filters, respectively. Figure 5 shows the differential pressures of the filters tested with respect to the filter dust loading. Filter dust loading is the accumulated respirable dust mass that was put through the scrubber during the individual filter tests, amassed from the upstream respirable dust concentrations, average dry scrubber airflow quantities, and test times.

The scrubber averaged greater than 95 percent dust removal efficiency with the disposable filters and had consistent dust removal efficiencies for the two airflows tested (Fig. 3). After eight hours of operation, the scrubber airflow quantity with the disposable filters could not be maintained above 4.00 m^3/s (8,500 ft^3/min), indicating that the fan reached its maximum 60-Hz fan motor frequency or horsepower rating. After the eighth hour of dust testing, the maximum scrubber airflow quantity that could be achieved was 3.97 m^3/s (8,420 ft^3/min) at a filter differential pressure of 2,610 Pa (10.5 in. w.g.). Figure 5 further illustrates decreasing scrubber airflow quantities with additional filter dust loading after eight hours of testing. Scrubber airflow quantities decreased to 3.80 m^3/s (8,056 ft^3/min) for 1.98 kg (4.4 lb) of filter dust loading and 2,690 Pa (10.8 in. w.g.) of filter differential pressure, and decreased to 3.60 m^3/s (7,630 ft^3/min) for 2.27 kg (5 lb) of filter dust loading and 2,750 Pa (11.0 in. w.g.) of filter differential pressure.

Operating the scrubber with the washable filters showed them to be less efficient and more inconsistent than the disposable filters (Fig. 4). The dust removal efficiency of these filters averaged 88 and 90 percent, respectively, for their prewash and post-wash test conditions. The efficiency of the prewash filters started out at 86 percent, peaked at 97 percent after five hours of testing and dropped off to 66 percent after 14 hours of testing. Scrubber airflow remained fairly steady during all the prewash filter dust testing. The efficiency of the post-wash filters started out at 95 percent and inconsistently dropped to 86 percent, at which time the airflow decreased noticeably to below 4.00 m^3/s (8,500 ft^3/min) for the final test. When washing these filters between the prewash and post-wash testing periods, the average personal and downstream pDR dust concentrations measured were 1.2 and 8.3 mg/m^3, respectively.

Figure 5 further illustrates that the prewash filters had lower differential filter pressures compared with the disposable filters and experienced no significant scrubber airflow reductions from 2.6 kg (5.7 lb) of filter loading with 2,010 Pa (8.1 in. of w.g.) of filter differential pressure. The post-wash filters exhibited notably higher filter differential pressures during testing, and scrubber airflow notably decreased to 3.69 m^3/s (7,820 ft^3/min) for 2.01 kg (4.4 lb) of filter dust loading and 2,690 Pa (10.8 in. w.g.) of filter differential pressure for the final test.

The results of the sound level measurements are shown in Fig. 6. This graph clearly shows that the scrubber operating with loaded filters had higher sound levels than with clean filters for similar scrubber airflow quantities. Sound levels were also higher at the scrubber outlet location compared with the scrubber inlet location. Because 90 dB(A) is the MSHA's permissible exposure level under 30 CFR Part 62.101 (MSHA, 2015a), the sound levels (labeled in Fig. 6) at 2.83 m^3/s (6,000 cfm) of scrubber airflow indicate that miners should not have noise exposures that exceed the permissible exposure level for airflow rates at or below 2.83 m^3/s (6,000 cfm). If the machine is used at airflows near the upper end of its operating range, miners working nearby could be overexposed to noise. However, miners' exposure would vary depending on the distance from and the time spent near the scrubber.

Underground field testing

After laboratory testing, the scrubber was returned to Fletcher's research facility for inspection and preparation for underground testing. Several modifications were made to the DS prototype to facilitate completion of the underground coal mine testing portion of the NIOSH contract. The primary modification needed was substituting and reprogramming an existing MSHA-approved remote control unit for the desired remote control unit tested in the laboratory, which was currently pending an MSHA approval for underground coal mine use. It was also decided to use only the disposable filters during underground testing, as they provided the highest respirable dust removal efficiency and they eliminated the option of generating respirable dust from being cleaned underground. NIOSH visited Fletcher's research facility to examine these modifications and to remeasure the dry scrubber airflow quantity output compared with the machine-selected airflow quantity with the new remote control unit. These pitot tube measurements were used to correlate a reliable sample location for measuring the scrubber airflow quantity underground. Scrubber field testing was conducted at two continuous miner sections in an underground coal mine. The field-testing primarily involved underground dry scrubber dust control and airflow evaluations without noise measurements.

Airflow measurements

NIOSH airflow measurements taken at Fletcher's research facility were again taken along the 32 equal area sampling grid inside the 122-cm-wide by 31-cm-high (48-in.-wide by 12-in.-high) discharge duct using a Series 166T telescoping stainless steel pitot tube and a 0- to 1.0-in. water gage magnehelic differential pressure gage (Dwyer Instruments Inc., Michigan City, IN). These measurements were taken at four measurement heights along eight holes spaced horizontally across the exhaust duct. The dry scrubber's VFD controller was operated at preset airflow quantities of 1.42, 2.83 and 4.25 m^3/s (3,000, 6,000 and 9,000 ft^3/min). Pitot tube measurements at the three dry scrubber preset air quantities were conducted with the straight exhaust duct and with the optional 90° angled discharge duct. Average duct velocity to grid point velocity ratios were examined for the most consistent and reliable sample locations for underground scrubber airflow measurements. A pitot tube measurement at a reliable sampling location was used to determine the scrubber airflow velocity during the underground field studies.

Airflow quantities to the face area cleaned by the scrubber were also measured during the study to indicate the scrubber's operational impact on face airflow quantity. A one-minute moving traverse was made over the cross-sectional area of the face curtain opening with a vane anemometer (Davis Instrumentation Mfg. Co., Baltimore, MD) without and with the scrubber turned on.

Underground dust sampling

Underground field-testing investigated the dust reductions realized from operating the dry scrubber downstream of the continuous miner at two producing mining machine units (MMUs). One MMU was on the right side of a nine-entry super section and the other MMU was on the right side of another 12-entry super section. Fish-tail ventilation was used at both super sections to supply intake air to the MMUs studied. The MMUs used blowing face ventilation with flooded-bed scrubbers on the continuous miners. In order to increase the dry scrubber operating time and data collection underground, the dry scrubber was placed in the last open crosscut of the section return to examine its effectiveness on lowering respirable dust concentrations at the face areas of entries 9 and 12, downstream of all mining activities. This test strategy minimized moving the scrubber around in the section while providing the least interference with production. Figure 7 illustrates the scrubber location in the last open crosscut of entry 9 at the first super section studied and the areas that were dust-sampled during the field studies. The optional 90° angled discharge duct was used during the underground studies to direct the scrubber's exhaust air along the blowing face ventilation curtain. Dust sampling locations sampled during the study included (Fig. 7): (A) the intake to the bolting machine; (B) the bolting machine near the left-side operators' location; (C) the last open crosscut just upstream of the scrubber; (D) the downstream face area cleaned by the scrubber (entry 9 or 12); and (E) the section return entry. The bolting machine was monitored to examine the respirable dust concentrations at this location when working upstream and downstream of the continuous miner during the production shift. The other dust sampling locations were used for evaluating the respirable dust reductions realized from operating the scrubber. The sampling instrumentation used at each sampling location during this field study was identical to those used in the laboratory (two CMDPSUs and one pDR), as described earlier. Respirable gravimetric concentrations used in this analysis were not adjusted to MSHA's MRE compliance sample equivalents (multiplied by 1.38).

The pDR's instantaneous dust concentration data were time-recorded every 10 seconds in its internal memory and downloaded to a computer after the sampling shift. The pDR real-time dust concentrations were gravimetrically calibrated by multiplying each 10-second reading by a gravimetric to pDR dust concentration ratio, determined by dividing their average concentrations measured over identical sampling periods. These adjusted pDR dust concentrations were used to determine dust concentrations during the particular mining activities. Time study and section location of the continuous miner and roof bolter machines were recorded during each sampling shift. This information was used to coordinate and determine the gravimetrically adjusted pDR dust concentrations during time segments of the scrubber operation and roof bolter activities with respect to the continuous miner operation. The dry scrubber was moved and parked outby in the section return entry when the continuous miner was cutting in return entries 9 and 12 so as not to inhibit shuttle car haulage. The dust samplers in the last open crosscut, the face area and the section return were also relocated while mining in return entries 9 and 12.

Field-test results

Pitot tube measurements taken inside the exhaust duct of the scrubber at Fletcher's research facility showed relatively consistent velocity profiles for the three scrubber airflow quantities tested with both exhaust configurations. Figure 8 shows the velocity profiles measured along the 32-grid sampling locations at the 1.42, 2.83 and 4.25 m^3/s (3,000, 6,000 and 9,000 ft^3/min) targeted scrubber airflow quantities with both the straight and 90° exhaust configurations. This graph illustrates a relatively consistent airflow velocity pattern at each of the grid locations with the most stable velocities measured in the center part of the exhaust duct (grid locations 12 through 20). The scrubber operating airflow quantities averaged 1.42, 2.73 and 3.90 m^3/s (3,000, 5,790 and 8,260 ft^3/min) for the three targeted airflow quantities with both exhaust configurations: straight and 90°. Average duct velocity to grid velocity ratios were also determined for each of the scrubber airflow quantities and both exhaust configurations tested. Figure 9 shows the average, minimum and maximum velocity ratios determined for each of the 32-grid sampling locations. As can be seen from this figure, some of the smallest velocity ratio variations were at grid locations 15, 16 and 19, having duct velocity to grid velocity ratios of 0.76, 0.85 and 0.71, respectively, with the lowest measured velocity ratio ranges of 0.04. As the airflow velocity ratio at location 16 was nearest the grid average, it was selected as the pitot tube location for measuring the dry scrubber airflow quantity underground. The scrubber airflow quantity was determined from multiplying the airflow velocity measurement by the 0.85 ratio and 0.4-m^2 (4-ft^2) duct area.

Table 2 shows the time-weighted average respirable dust concentrations measured with respect to the continuous mining activities at both of the sections studied. These concentrations represent gravimetrically calibrated pDR dust levels averaged for the time periods when the roof bolting machine was operating upstream and downstream of the continuous mining machine. Average dust concentrations at the roof bolting machine at sections 1 and 2 were 0.59 and 0.17 mg/m^3, respectively, when operating upstream of the continuous miner, compared with 1.80 and 1.60 mg/m^3, respectively, when it was operating downstream of the continuous miner and upstream of the dry scrubber. The dust concentrations at the last open crosscut of the scrubber location at sections 1 and 2 were 2.77 and 2.43 mg/m^3, respectively, when the roof bolting machine was upstream of the continuous miner, compared with 1.85 and 1.35 mg/m^3, respectively, when the bolting machine was downstream of the continuous miner. The higher crosscut dust concentrations measured when the roof bolter was upstream of the continuous miner was likely due to the continuous miner operating physically closer to the last open crosscut sampling location, thereby reducing the time for dust dilution and dispersion of the continuous miner return concentrations by the section ventilation.

Table 2 also shows that the scrubber reduced the dust concentrations at the face areas downstream of the continuous miner for all cuts by 49.1 and 50.5 percent at sections 1 and 2, respectively. At section 2, when the roof bolter was in entry 12 downstream of the continuous miner and dry scrubber, the dust reduction at the face was somewhat lower at 36.8 percent. The average roof bolter machine dust concentration, 1.10 mg/m^3, was nearly identical to the average face dust concentration, 1.06 mg/m^3, when downstream of the continuous miner and scrubber. The lower percentage of dust reduction realized at the face when the bolting machine was present may have been due to some additional dust generated by the bolting machine in this face area.

In order to ascertain the scrubber's respirable dust collection efficiency underground, the face area sampling package was placed directly into the scrubber exhaust discharge air for a short period of time (2 to 5 minutes) at the end of several shifts to determine its respirable dust collection efficiency (concentrations not shown in Table 2). The measured scrubber exhaust concentrations at sections 1 and 2 averaged 0.13 and 0.01 mg/m^3, respectively, while their corresponding upstream dust concentration averaged 1.87 and 1.08 mg/m^3, thereby yielding scrubber dust collection efficiencies of 93.2 and 99.2 percent, respectively. These dust collection efficiencies were found to be very similar to the scrubber's laboratory test results with similar disposable filters. Consequently, the scrubber's reduced dust reduction effectiveness at the face sampling locations demonstrate that its clean exhaust discharge air was being mixed with some of the dustier section return air to ventilate the face area.

Airflow quantity measurements at the last open crosscut and face areas likewise showed that the scrubber cleaned a small amount of the section return air and mixed this cleaned air with some of the return air for ventilating the face. Airflow quantities in the last open crosscut during these studies ranged from 5.32 to 13.1 m^3/s (11,270 to 27,720 ft^3/min), while the scrubber was operated at airflow quantities of 1.28 to 2.31 m^3/s (2,720 to 4,900 ft^3/min). Initial ventilation airflow quantities delivered to the face areas ranged from 0.784 to 2.31 m^3/s (1,660 to 4,890 ft^3/min) without the scrubber operating and were enhanced by the scrubber to an operating range of 1.09 to 3.88 m^3/s (2,300 to 8,220 ft^3/min), thereby providing a 1.4 to 1.7 increase over the initial face ventilation airflow quantities without the scrubber. These face airflow changes from operating the scrubber also indicate that its exhaust airflow was being mixed with some of the dusty return airflow.

Several scrubber operation issues were observed during the study at section 1. The scrubber unexpectedly shut down and was restarted during nearly half of the cut periods at section 1, and sometimes its measured airflow quantity deviated up to nearly 2,760 cfm from its preprogramed targeted amount. These operational malfunctions were attributed to communication issues encountered from the substitution of an approved MSHA underground coal mine remote control unit with the original, unapproved scrubber remote control unit, which had been thoroughly and successfully tested in the laboratory. The original scrubber remote control unit was pending an MSHA approval and could not be used during the underground coal mine field-testing. During the second field study at section 2, the scrubber was operated more continuously by using the fan motor's frequency control mode, thereby eliminating the intermittent dry scrubber shutdowns experienced during the first field study. The scrubber's fan motor was operated at 25 to 35 Hz to deliver scrubber airflows of 1.28 to 2.13 m^3/s (2,720 to 4,510 ft^3/min) at differential filter pressures of 473 to 971 Pa (1.9 to 3.9 in. w.g.).

The scrubber operating parameters measured at section 2 indicate that the disposable filter cartridges did not reach their fully loaded dust capacity during underground testing. At section 1 the dry scrubber was operated for 461 minutes with an average dust concentration of 2.24 mg/m^3, and at section 2 the dry scrubber was operated for an additional 509 minutes with an average dust concentration of 1.90 mg/m^3. Previous laboratory testing indicated that the disposable filters approach their useful life when they were loaded with an average dust concentration of 17.8 mg/m^3 for 729 minutes. An accumulated filter dust mass loading of 2.27 kg was determined from this laboratory testing to reach the maximum differential filter pressure of 2,750 Pa (11.0 in w.g.) at 3.60 m^3/s (7,630 ft^3/min) of airflow quantity. Estimation of filter dust loading times or useful filter life at various scrubber airflows and dust concentrations less than or equal to these maximum laboratory dry scrubber operating parameters can be calculated using the following equation:

$$Filter\ Dust\ Loading\ Time(hr)=\frac{2.27(kg)\times 1{,}000{,}000\left({}^{mg}/_{kg}\right)}{Dust\ Concentration\left({}^{mg}/_{m^3}\right)\times Airflow\ Quantity\left({}^{m^3}/_{s}\right)\times 3600\left({}^{s}/_{hr}\right)} \quad (2)$$

Thus, operating the scrubber at 4,000 ft^3/min in dust concentrations of 2 mg/m^3, comparable to the underground field study conditions, indicates a longer filter dust loading time of 167 h, compared with the 16.2 h of actual underground field-testing time. Given that the scrubber on the last shift of testing exhibited a maximum filter differential pressure of 971 Pa (3.9 in. w.g.) at 2.13 m^3/s (4,510 ft^3/min) while operating at 35 Hz, these filters did not appear to be at their maximum filter life compared with laboratory test results.

Conclusions

NIOSH laboratory testing of the Fletcher DS dry scrubber showed that it averaged greater than 95 percent dust removal efficiency with disposable filters, and 88 and 90 percent, respectively, with washable filters in their prewash and post-wash test conditions. Although the washable filters can be reused, washing them generated notable amounts of dust. The personal and downstream dust concentrations measured averaged 1.2 and 8.3 mg/m^3, respectively, over the 10-min washing period. Laboratory dust testing showed that the scrubber fan also maintained a relatively consistent airflow near the targeted 1.42 and 4.25 m^3/s (3,000 and 9,000 ft^3/min) airflow rates until reaching 2,610 Pa (10.5 in. w.g.) of filter differential pressure at 3.97 m^3/s (8,420 ft^3/min) of scrubber airflow quantity. At this point, the scrubber airflow decreased with additional dust loading because the fan had reached its maximum horsepower rating with the VFD operating the fan at 60-Hz motor frequency. Sound level measurements taken of the scrubber in the laboratory showed that the outlet side of the scrubber was noisier, and the loaded filters increased sound levels compared with clean filters at the same airflow quantities. With loaded filters, the scrubber reached a 90 dB(A) sound level at 2.83 m^3/s (6,000 ft^3/min) of scrubber airflow, indicating that miners should not be overexposed in relation to MSHA's permissible exposure level of 90 dB(A) at or below this airflow quantity.

Field-testing the dry scrubber with disposable filters at two underground coal mine sections showed that it could clean a portion of the section return air and provide dust reduction of about 50 percent at the face area downstream of the continuous miner operation. The average roof bolting machine dust concentrations at sections A and B were 0.59 and 0.17 mg/m^3, respectively, when operating upstream of the continuous miner, compared with 1.80 and 1.60 mg/m^3, respectively, when it was operating downstream of the continuous miner and upstream of the scrubber. A 36.8 percent dust reduction was measured at section B when the roof bolter was operating downstream of the continuous miner in the face area being cleaned by the scrubber. The scrubber's dust collection efficiencies at sections A and B were 93.2 and 99.2 percent, respectively, showing that the exhaust airflow was mixed with some of the dusty return airflow being delivered to the face. This airflow mixing was further exhibited by the scrubber's 1.4 to 1.7 face airflow quantity improvement over the initial airflow quantities without the scrubber operating. Therefore, the DS dry scrubber appears to be a new viable dust control method to combat roof bolter dust exposures when operating downstream of the continuous miner.

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Figure 1.
The self-tramming Dry Scrubber (DS) prototype.

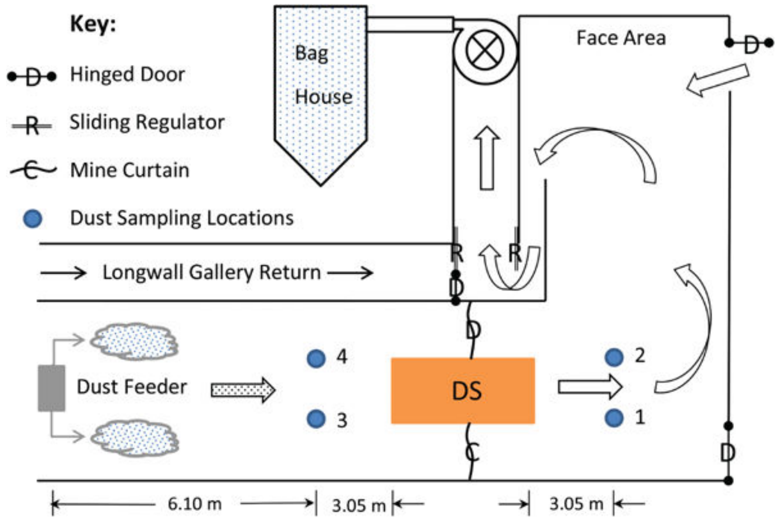

Figure 2.
Plan view of the Dry Scrubber (DS) testing location in the continuous miner gallery (not to scale).

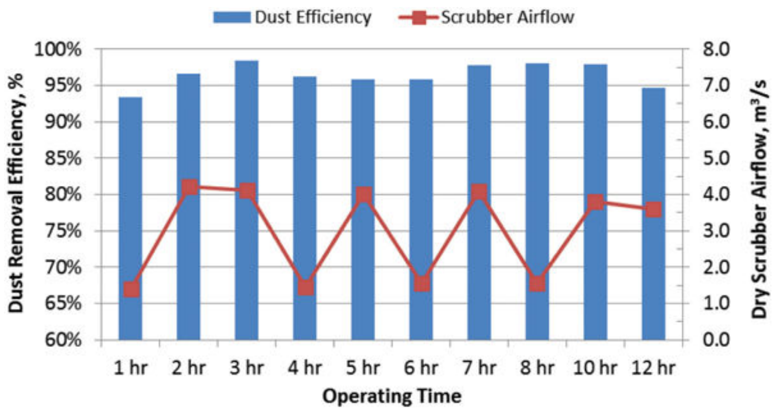

Figure 3.
Disposable filter dust efficiency and airflow test results with respect to operating time.

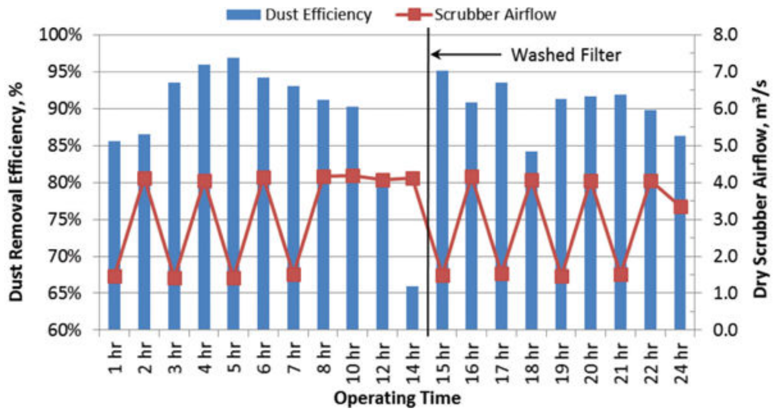

Figure 4.

Washable filter dust efficiency and airflow test results with respect to operating time.

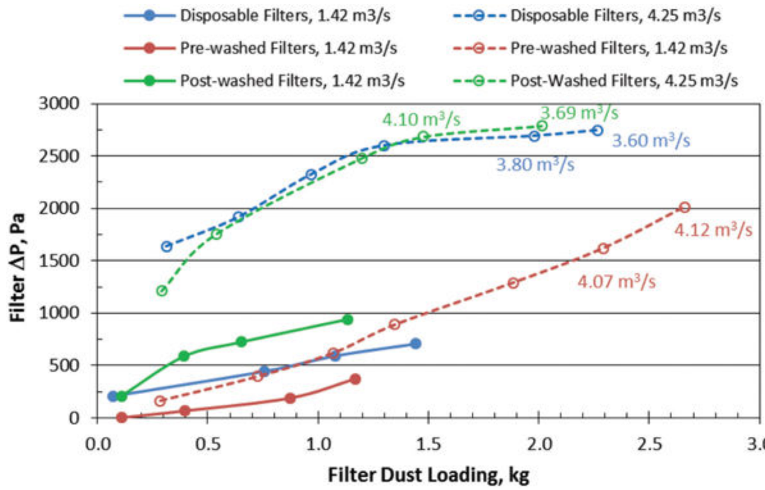

Figure 5.

Differential pressure of scrubber filters with respect to filter dust loading (labeled points show the average scrubber airflow quantities measured for the last two filter dust tests).

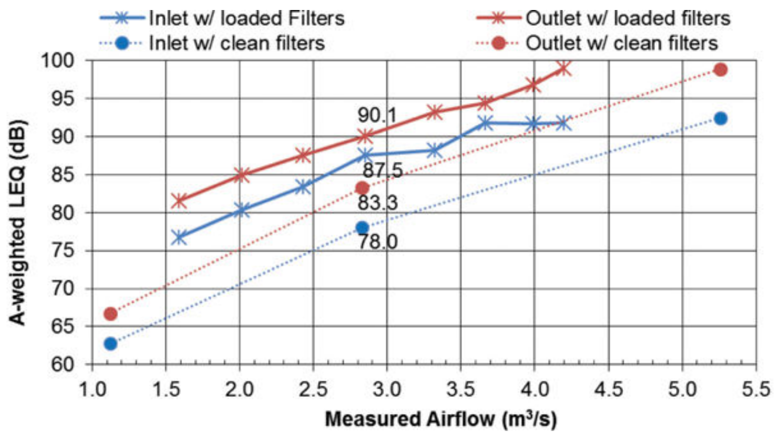

Figure 6.

Sound level measurement results for the Dry Scrubber with clean and loaded filters.

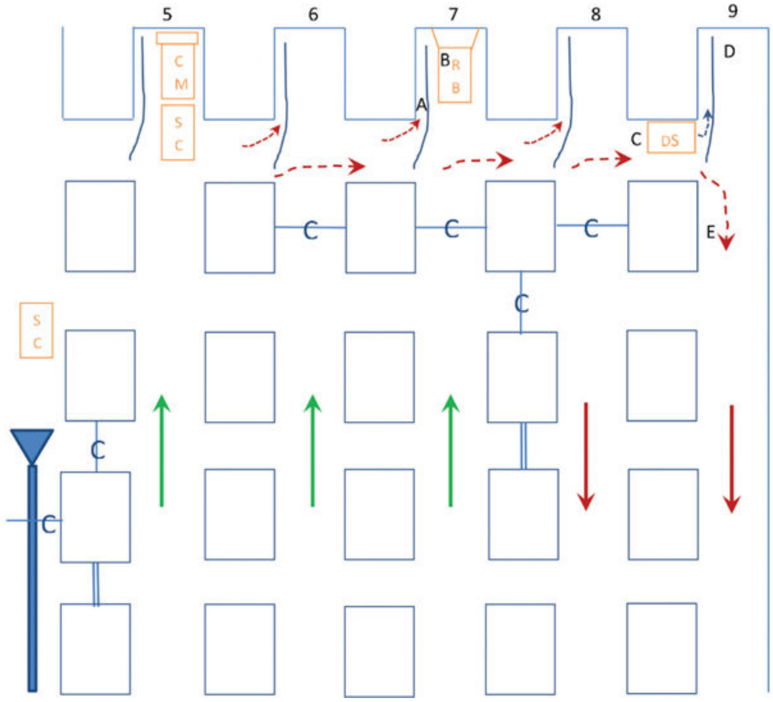

Figure 7.

Plan view of DS operation downstream of the continuous mining machine on the 9-entry super section studied using blowing face ventilation (right-side MMU, capital letters indicate dust sampling locations).

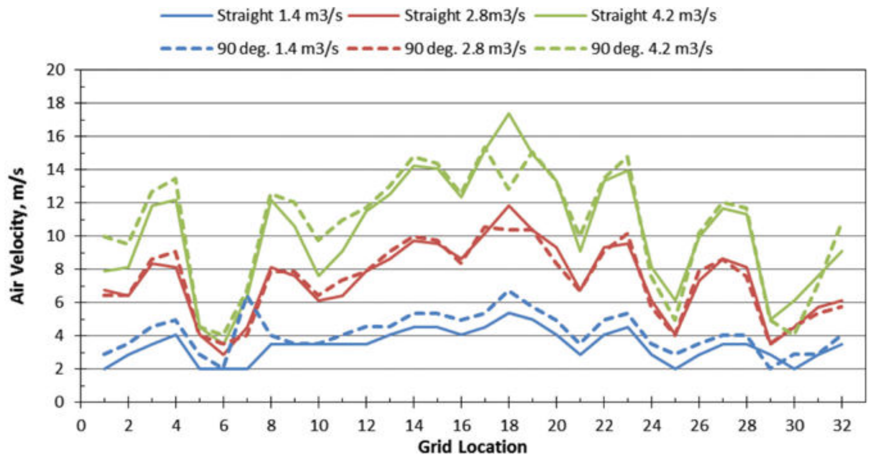

Figure 8.
Air velocities measured along the DS's exhaust duct sampling grid for both exhaust configurations.

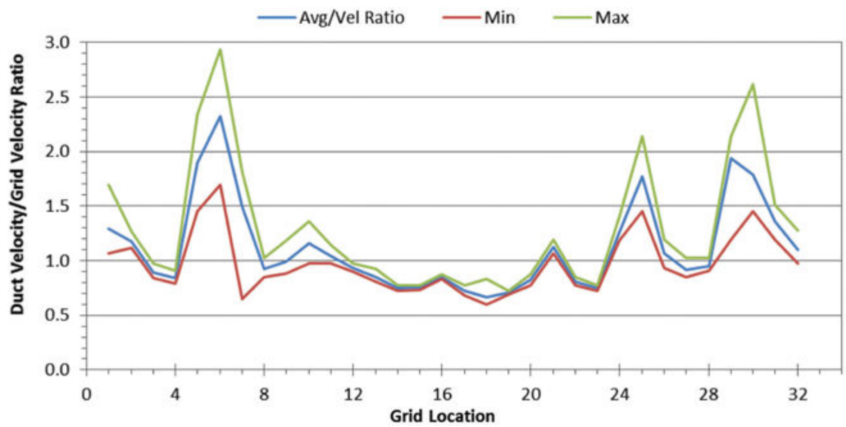

Figure 9.
Average duct velocity to grid velocity ratios measured along the DS's exhaust duct sampling grid.

Table 1

Comparison of hot wire and pitot tube measurements to vane anemometer discharge measurements for the Fletcher DS dry scrubber.

Airflow instrument, quantity	Testing period	DS target of 1.42 m^3/s	DS target of 4.25 m^3/s
Hot wire (vane anemometer), m^3/s	Initial DS	1.05 (1.11)	4.32 (4.33)
Pitot tube (vane anemometer), m^3/s	Initial DS	1.01 (1.16)	4.04 (4.38)
Hot wire (vane anemometer), m^3/s	Modified DS	1.42 (1.45)	4.34 (4.18)
Pitot tube (vane anemometer), m^3/s	Modified DS	1.34 (1.42)	4.03 (4.19)

Table 2

Time-weighted averages of roof bolter and DS dust concentrations with respect to the continuous-miner location. (DS = Dry Scrubber, CM = Continuous miner, NA = Not available)

Bolter location	Mine test section (MMU)	Intake dust conc. to roof bolter A mg/m^3 (cuts)	Roof bolter dust conc. B mg/m^3 (cuts)	Crosscut dust conc. upstream DS C mg/m^3 (cuts)	Face dust conc. down-stream DS D mg/m^3 (cuts)	Section return dust conc. E mg/m^3 (cuts)	DS face dust reduction efficiency[b] (percent)
Upstream	1[a]	0.54 (6)	0.59 (6)	2.77 (6)	1.32 (6)	1.99 (6)	52.9
CM	2	0.22 (9)	0.17 (9)	2.43 (5)	0.91 (5)	0.96 (5)	59.9
Downstream	1[a]	1.96 (6)	1.80 (6)	1.85 (7)	0.99 (7)	1.51 (7)	46.3
CM and upstream DS	2	1.58 (4)	1.60 (4)	1.35 (3)	0.66 (3)	1.20 (3)	50.7
Downstream	1[a]	NA (0)	NA (0)	NA (0)	NA (0)	NA (0)	NA (0)
CM and downstream DS	2	1.00 (4)	1.10 (4)	1.69 (4)	1.06 (4)	1.25 (4)	36.8
Average of all cuts	1[a]	1.32 (12)	1.26 (12)	2.24 (13)	1.13 (13)	1.72 (13)	49.1
	2	0.71 (17)	0.71 (17)	1.90 (12)	0.88 (12)	1.11 (12)	50.5

[a]The DS scrubber intermittently kicked off and was restarted during nearly half of the cuts studied.

[b]Determined as the time-weighted average of the DS face dust reduction efficiencies for the individual cuts.