Development of a canopy air curtain to reduce roof bolters' dust exposure

by J.M. Listak and T.W. Beck

Abstract The U.S. National Institute for Occupational Safety and Health (NIOSH) conducted a study to determine the effectiveness of a filtered air delivery system to reduce respirable dust exposure of roof bolter operators in underground coal mines. When performing roof bolting operations, roof bolter operators may experience exposure to high levels of respirable dust during a working shift, especially when working downwind of the continuous mining machine. While drilling and installing roof bolts, this filtered air system supplies a clean curtain of air over the roof bolter operator by means of a plenum mounted beneath the canopy. This experimentally designed air curtain, adapted for roof bolting machines used in this study, is based upon previous design prototypes, computational fluid dynamics (CFD) simulations and trial-and-error testing. Both the prototype and final designs were tested in the full-scale mining galleries at the Office of Mine Safety and Health Research (OMSHR) in Pittsburgh, PA before being taken underground for field testing. Test results of the system in both laboratory and field studies show reductions in operator exposure to respirable dust when the operator is positioned directly under the protected zone of the canopy.

Introduction

Underground coal mine roof bolter operators are at risk of excessive exposure to respirable coal and silica dust, second only to continuous miner operators, based upon the U.S. Mine Safety and Health Administration (MSHA) personal dust samples (MSHA, 2009). Dust collectors on roof bolting machines, if maintained properly, effectively minimize dust exposures during drilling and bolting activities. However, due to mining sequencing, there may be times during a working shift when roof bolter operators must work downwind of the continuous mining operation. When this scenario occurs, the dust from the continuous miner enters the roof bolting workplace, potentially exposing the operators to high levels of respirable dust. In addition, the bolting operation itself can contribute to higher respirable dust concentrations in the worker's area if dust collectors are not maintained, adding to operator exposure. To lessen the operator's dust exposure when these conditions occur, a plenum mounted under the roof bolter's protective canopy has been developed to supply filtered air over the operator as bolting duties are performed. This filtered air is delivered to the plenum via tubing connected to a blower that is mounted on the roof bolting machine.

The roof bolting procedure requires the operator to stand under a support canopy for protection from loose roof rock as holes are drilled into the mine roof for the installation of roof bolts (Fig. 1).

This canopy is fixed to the drill boom and continually offers the operator protection from loose debris as the boom is repositioned for each new hole. Based upon time studies conducted for this study, nearly 66% of the operator's drilling time is spent under this canopy during a complete cycle of bolting. The canopy, therefore, provides an ideal location for installing a device to protect the operator from respirable dust. The underside of the roof canopy serves as a mount for such a device to deliver a filtered air supply over the operator during drilling activities. This device or canopy air curtain (CAC) serves as a plenum to blow a constant stream of fresh air over the breathing zone of the operator. The air supply will act as a "curtain" of fresh air for a zone of protection from the contaminated air around the bolter, regardless of the dust source (Fig. 2).

Although a new application for roof bolting machines, air curtain technology

Figure 1

Roof bolter operator under roof canopy during roof drilling.

Figure 3

Original square air curtain design, by Donaldson Company, Inc.

for continuous miner operator cabs was originally developed under a U.S. Bureau of Mines contract in the 1970s by the Donaldson Company Inc. (1975). Before the advent of radio remotes for controlling the operation of continuous mining machines, the operators were located in an onboard control cab at the rear of the continuous miner. Close proximity of the cab to the cutter head subjected the operators to high levels of respirable dust during mining. In an attempt to reduce dust exposure to the operator, a contract was awarded to develop a device to provide a source of fresh air for these operators. This device was designed to be compatible with the mining equipment and offer protection from dust exposure while minimally affecting operator safety, comfort and mobility within the cab area. The final working design consisted of a square plenum, blower and filter, and connective tubing. The plenum housing was made from fiberglass and used perforated plate and screen mesh as an air diffuser. The inlet port was tapered, as well as the area over the air diffuser. The surface of the air diffuser had dimensions of 43.2 x 43.2 cm (17 x 17 in.). Figure 3 shows the Donaldson air curtain design. Field testing of the air curtain in continuous miner cabs showed reductions in dust exposure from 30% to 75% depending upon the amount of time the operator spent in the protected zone.

In the early 1980s, the Mining Research and Development Establishment (MRDE) of the National Coal Board in Great Britain (NCB) (MRDE, 1981) tested Donaldson's air curtain design in the cabs of heading/ripping machines to determine its effectiveness in reducing operator exposure to respirable dust. The MRDE research found that entry velocities in excess of 0.51 m/s (100 fpm) could infiltrate the protected area under the cab, "pushing" dust into the operator's breathing zone. Through design modifications, the MRDE produced an air curtain that reduced dust by up to 70% in an entry airflow velocity of nearly 1.5 m/s (300 fpm).

Another study (Volkwein et al., 1982) showed that the Donaldson air curtain was applicable for dust reductions on equipment other than continuous mining machines. Volkwein showed dust reductions of up to 50% on a gathering-arm loader operator in a salt mine. However, as with other studies, results showed that higher entry velocities reduced the effectiveness of the air curtain.

Although Donaldson proved that the air curtain concept could be an effective means to reduce operator dust exposure, the 10.2 cm (4 in.) thickness of the original design did not allow adequate headroom beneath some operator's canopies. In response to this problem, Donaldson was awarded another contract in 1983 (Donaldson Company Inc., 1987) to design an air canopy that would be thinner, yet provide the necessary airflow to be as effective as the original design. The newer design had the same-sized diffuser, but the smaller thickness required different inlet geometry. The newly designed air curtain performed as well as the original and gave impetus for investigating air curtain use under the canopies of roof bolting machines. NIOSH researchers (Goodman and Organiscak, 2001) conducted tests on the new design to determine its effectiveness to reduce respirable dust for roof bolter operators under various simulated mine conditions. The unit was tested at different distances below the diffuser plate, as well as in different entry air velocities. The environment in which the unit was tested had respirable dust concentrations of approximately 4 mg/m^3. The results of this study showed respirable dust reductions of up to 62%. A smaller air curtain with a rectangular shape, 61 x 25.4 cm (24 x 10 in.), was subsequently field tested to determine the feasibility of installing, operating and maintaining the complete system on a roof bolting production cycle (Goodman et al., 2006). Although the plenum was too small to offer dust reduction to the operators, the tests showed that the system could function on a roof bolting machine in an underground environment.

The Donaldson design proved that dust reductions can be achieved using a filtered air delivery system. However, the square

Figure 2

Roof bolter operator protected by clean airflow provided by canopy air curtain.

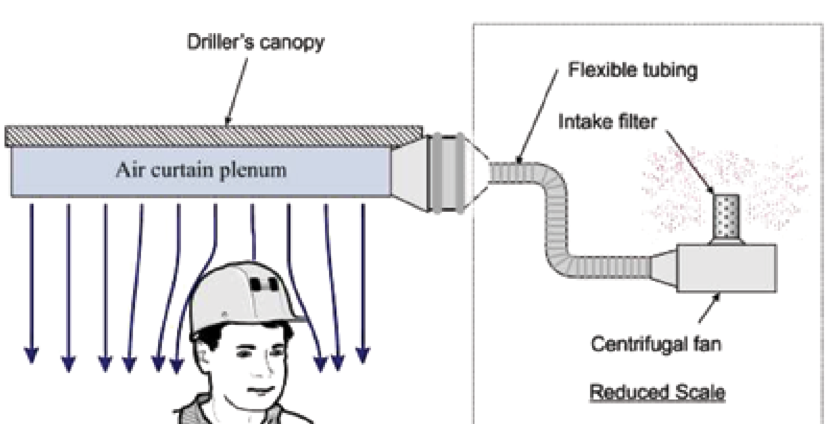
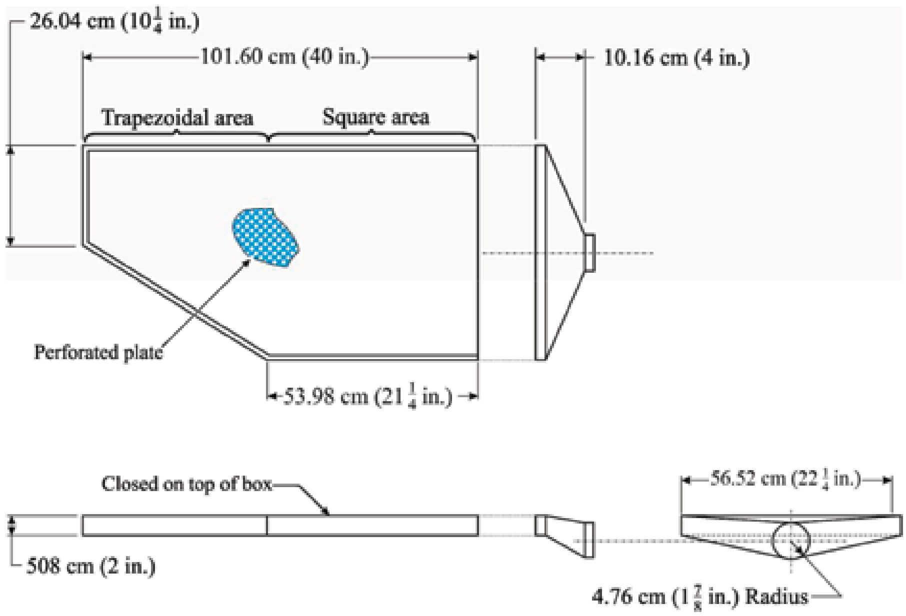


Figure 4

Original air curtain designed for a roof bolter canopy.



geometry of the plenum, if used on a standard roof bolter canopy, would only provide partial coverage of the worker's operating area while under the canopy. Therefore, a new prototype was developed that would offer greater coverage of filtered air beneath any area of the roof canopy.

Prototype design and testing

Parameters for the newly designed unit began with the shape of the plenum. The typical canopy dimensions of roof bolters sized for coal seam heights up to 1.83 m (6 ft) are 101.6 x 50.8 cm (40 x 20 in.). The dimensions also include a tapered angle reducing the outermost dimension to 25.4 cm (10 in.). These dimensions were used to define the geometry of a newly developed plenum. A height restriction of 5.1 cm (2 in.) was required to provide head clearance for operators beneath the canopy. The remaining components consisted of a centrifugal fan (American Fan, model AF-10), sized for delivering air to the plenum, and a filter. The fan used in laboratory testing provided 0.165 m^3 at 0.25 kPa (350 CFM at 1 in WC). A filter (P12-3990, Donaldson Co., Inc., Minneapolis, MN) was used to clean the air before it passed through the fan. Tubing with a diameter of 10.2 cm (4 in.) connected the fan/filter assembly to the plenum. As with the Donaldson design, the success of the system depends on a uniform distribution of air flowing over the operator to provide a protected area beneath the entire canopy. Therefore, the initial plenum design was based upon the Donaldson units. A perforated plate with a 13% open area, backed by 180-μm (80-mesh) screen, was used as the outflow air diffuser, covering the entire underside of the plenum. The inlet portal shape and location had to be changed to allow for canopy movement and to conform to the mast location on the roof bolting machine. Figure 4 shows the first prototype unit. The figure shows two distinct areas that will be referenced throughout the paper, the trapezoidal area and the square area. Although these regions are contiguous, the distinction is shown in Fig. 4 to better direct the reader when references are made to plenum performance.

To evaluate the plenum design, air velocity exiting the diffuser was measured to determine airflow uniformity. A 10.2-x-10.2-cm (4-x-4-in.) grid was constructed and mounted beneath the plenum to perform repetitive velocity measurements of the new and subsequent designs. The grid was located 25.4 cm (10 in.) below the plenum, which falls within the breathing zone range of a worker wearing a hardhat. The velocity measurements beneath the unit were taken using a hotwire anemometer (TSI Inc., Model 8346) as shown in Fig. 5.

Using the 136-point velocity values from each grid traverse, velocity profiles were created to show the distribution of air exiting the plenum. On the early plenum designs, velocity profiles showed that the air flowing from the perforated plate was very uneven. As an example, Fig. 6 shows

Figure 5

Velocity measurement grid 25.4 cm (10 in.) beneath the plenum.

Figure 6

Velocity profile of original CAC design.

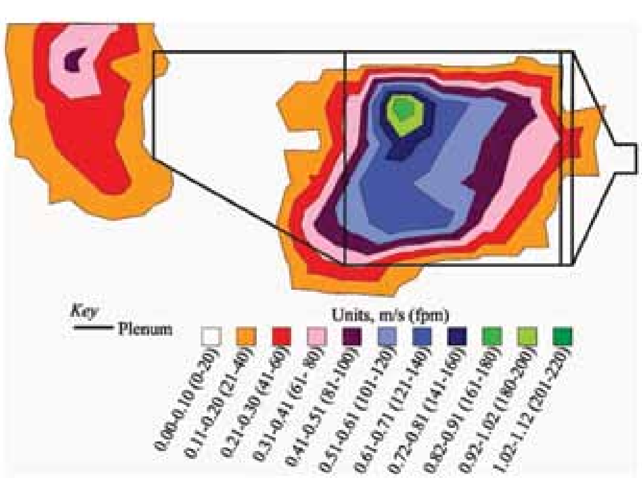


Figure 7

Prototype modified based upon CFD analysis.

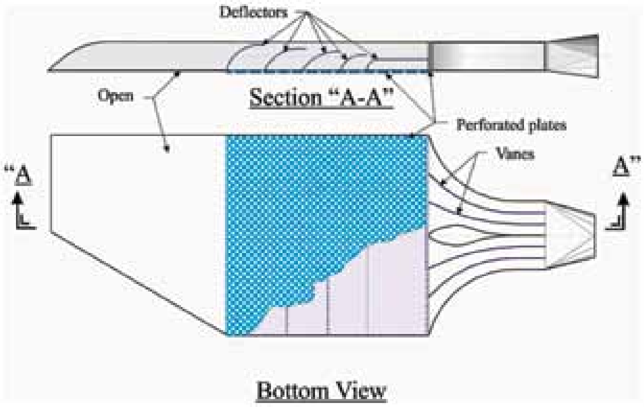
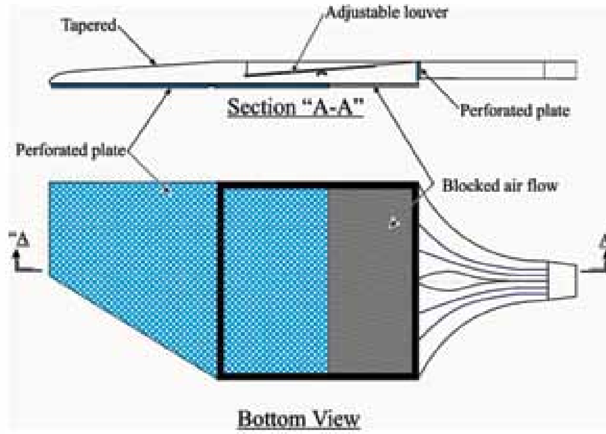


Figure 8

The final CAC design.



the velocity profile of the original plenum design. As shown in the figure, most of the airflow was concentrated to the square area of the plenum. A maximum velocity of 1.12 m/s (220 fpm) was measured. In the trapezoidal area of the plenum, the airflow exited on an angle out beyond the outer perimeter of the unit. Little to no flow was measured directly beneath the trapezoidal area of the plenum.

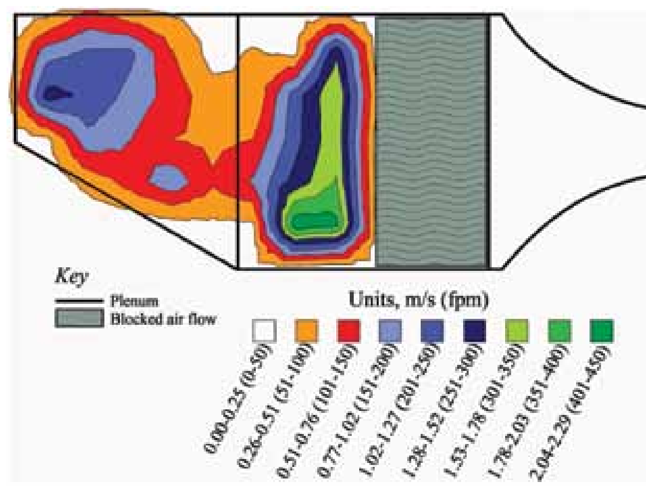
Testing also included dust measurements in the area where an operator would perform drilling duties. Although there was poor clearance overall, point measurements consistently showed that an air velocity from the plenum of 0.51 m/s (100 fpm) would provide dust clearance (> 50%) at an entry velocity of 0.31 m/s (60 fpm). As can be seen in Fig. 6, the velocity contour area greater than 0.51 m/s (100 fpm) is limited to a small area under the plenum.

To try to improve airflow distribution, the unit was disassembled and various baffles, inflow vanes and flow straighteners were added in attempts to direct the air through the device for better distribution. All initial modifications failed to produce uniform airflow. Therefore, to better determine the dynamics of the airflow within the plenum and make the necessary changes, the unit was assessed by a ventilation computer simulation company using computational fluid dynamics (CFD) evaluation. The initial CFD results showed deficiencies in the original design. Based on these results, CFD modifications were made to the prototype in an attempt to provide even flow from the unit. Several iterations were performed until the computer model showed that the modifications inside the plenum would provide the best flow from the unit. After the design changes were made (Fig. 7), the unit was retested in the laboratory to determine the velocity profile beneath the unit. Although there was improvement over the original design, the distribution of air beneath some areas of the unit was still too low in velocity to be effective for protection against dust infiltration. To improve flow, CFD simulators suggested a design change to the unit that would increase the vertical height of the plenum. This change was not an acceptable modification, due to the overhead clearance requirement for operator comfort.

After incorporating some of the CFD modifications, an angled plate with an adjustable louver was installed inside the square area of the unit to regulate airflow. The perforated plate over the square was removable, allowing for adjustment of the louver. The trapezoidal section was also tapered externally to force airflow downward. This design resulted in better flow, and preliminary in-mine tests were planned. Operational problems at the mine proved problematic, and the field testing was inconclusive. However, the field testing provided information that led to another positive change.

Figure 9

Velocity profile of the final design.



The area of the canopy nearest the mast hung over the machine and observation showed that when the plenum was mounted beneath the canopy, air was not flowing over the operator, but rather onto the tool tray of the machine. As a result, this area of the perforated plate was blocked off, shifting all flow forward and, thus, creating a smaller area from which to flow, resulting in higher velocity. Figure 8 shows all the modifications made to the final design. After the modifications were made, velocity measurements were taken and are shown in Fig. 9. In the new design, the velocity contours greater than 0.51 m/s (100 fpm) cover an area of approximately 70%. An area of low-velocity contours is obvious in the transition zone between the square and trapezoidal areas. Dust samples were measured in this zone and will be discussed in a subsequent section of this paper.

The final prototype was the result of an evolutionary experimental design process. The modifications were based upon previously designed prototypes (USBM contracts pre-

Figure 10

NIOSH mine gallery test setup configuration.

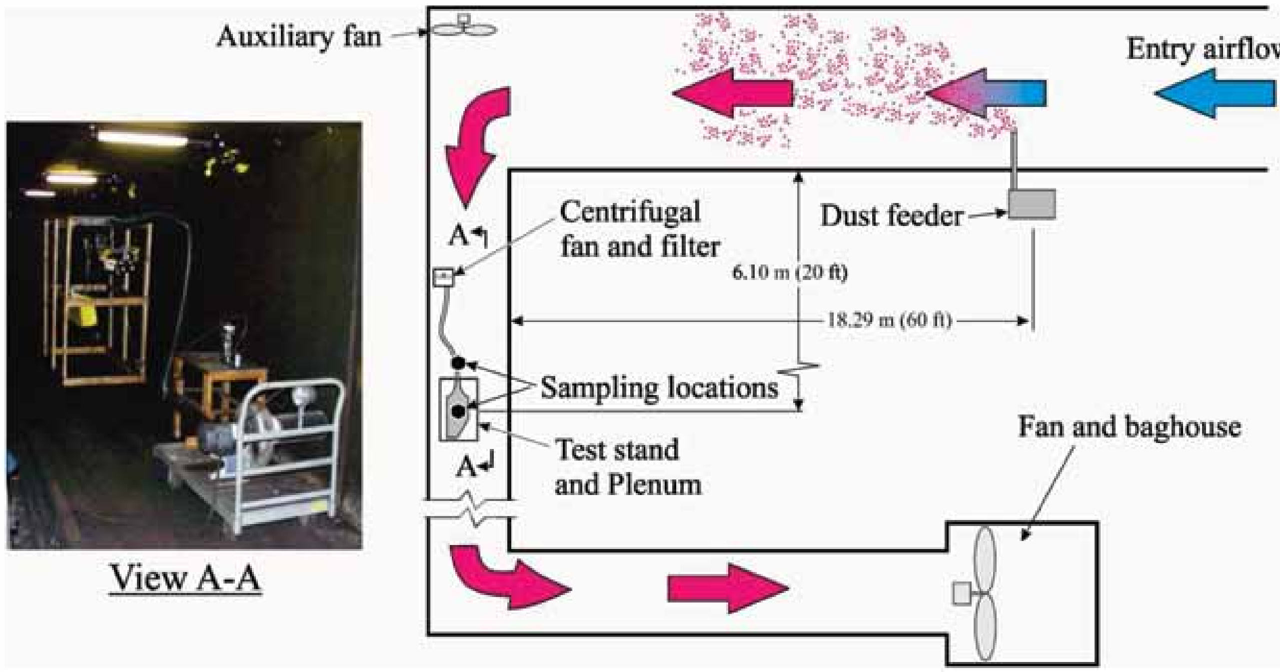
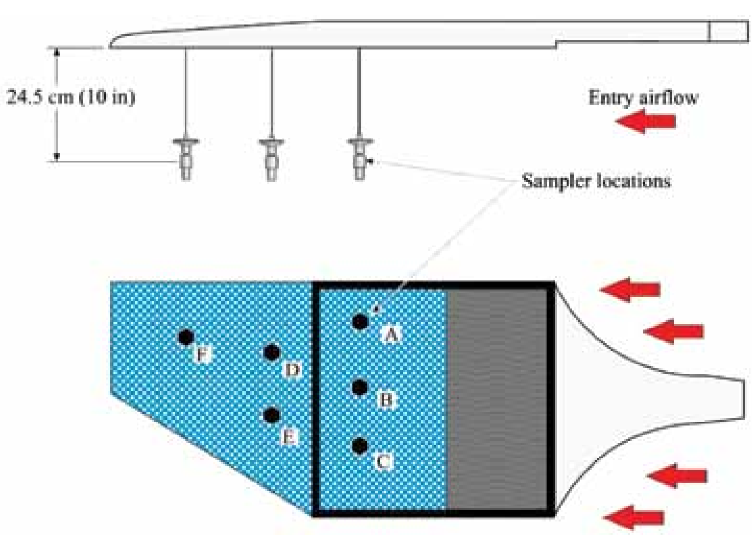


Figure 11

Dust sampling instrument locations under plenum.



viously cited), CFD simulations and trial-and-error testing. Changes included perforated plate percentage open, air inlet location and geometry, internal baffles and vanes, and flow straighteners (fine mesh screen and honeycomb cell).

Experimental design

Laboratory tests were conducted on the final plenum design to determine the zone of protection and the amount of respirable dust that was reduced. These tests were conducted in the full-scale mine simulation gallery at NIOSH Pittsburgh. The tests measured respirable dust concentrations at locations under the filtered air supplied by the plenum and outside the plenum in the gallery entry. Three entry velocities were also examined to determine whether faster entry air moving into the plenum's downward airstream would reduce the effectiveness of the system. The NIOSH test gallery simulates in-mine parameters including entry size, airflow, air velocity and dust concentrations. To simulate the use of the air curtain under a roof bolter canopy operating in a 1.83-m (6-ft) coal seam, a wooden test frame was constructed in the gallery. The test frame's mount for the air curtain was 1.7 m (67 in.) from the gallery floor, 0.58 m (23 in.) from the roof and 1.27 (50 in.) from the left side of the entry. The dimensions of the gallery in this location are 2.29 m (90 in.) high by 1.98 m (78 in.) wide. The plenum was mounted to the underside of the test frame for the tests.

The frame was positioned in the return airway of the gallery approximately 24.4 m (80 ft) downwind of a vibratory dust feeder (Vibra Screw Inc., Totowa, NJ). The respirable dust (Keystone Mineral Black, 325BA, Keystone Filler and Manufacturing Co., Muncy, PA) was fed into the airstream upwind of the test stand using the dust feeder. An auxiliary fan was also used in the entry to facilitate mixing of the dust before it reached the sampling instruments. A dust concentration of approximately 6 mg/m^3 was maintained for each test velocity. The use of this concentration was based upon a previous NIOSH study showing return concentrations of continuous miners using scrubbers (Listak et al., 2010). The test setup is shown in Fig. 10.

The dust sampling instruments consisted of gravimetric samplers and a personal DataRam (pDR 1000, Thermo Fisher, Franklin, MA). To measure dust levels beneath the canopy, six gravimetric samplers were positioned in spatial locations, 25.4 cm (10 in.) beneath the plenum. Physically, 25.4 cm (10 in.) is in the range of the typical breathing zone

Figure 12

Dust samplers relative to air velocity under plenum.

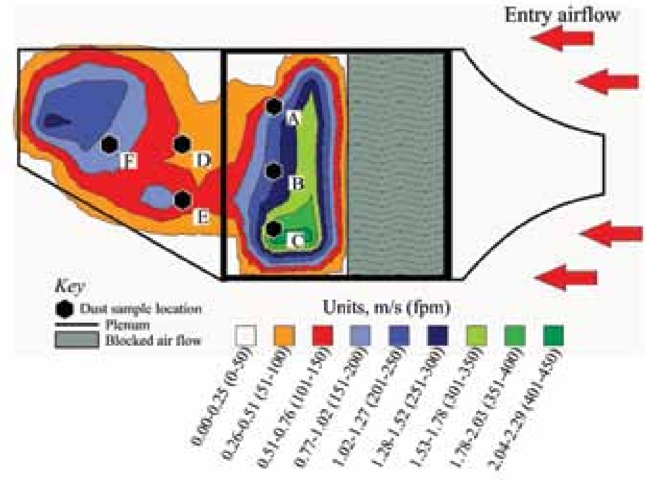


Figure 13

Relative dust concentrations, showing standard error bars, under the plenum versus outside the plenum (i.e., entry).

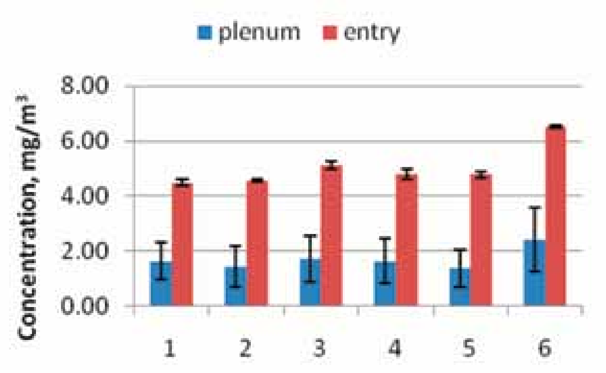


Table 1

Dust concentration averages from the two test locations at 0.3 (60 fpm).

	Velocity test dust averages, mg/m^3	
Test	**Plenum**	**Entry**
1	1.62	4.48
2	1.41	4.57
3	1.70	5.13
4	1.63	4.78
5	1.36	4.56
6	2.42	6.52

of an operator wearing a hardhat. The samplers were spaced laterally to measure dust at locations within an operator's range of motion while performing drilling duties (Fig. 11).

The entry dust was measured using two gravimetric samplers and a personal DataRam (pDR). This sampling array was positioned 1.52 m (5 ft) upwind of the plenum. Tests were conducted prior to introducing plenum airflow to ensure that dust concentration in both sampling positions (under the plenum and outside in the entry) were the same. The pDR was used to continually monitor dust feeder concentrations. The feeder was adjusted to keep concentrations at approximately 6 mg/m^3 throughout the testing of the three different entry velocities.

Six 30-min tests were conducted at velocities of 0.05, 0.3 and 0.61 m/s (10, 60 and 120 fpm) at the test area. These velocities were selected to reflect velocities that may be experienced in a typical roof bolter's workplace. Test velocities in the gallery at the test stand were established, measured and maintained using an ultrasonic anemometer (WindSonic, Gill Instruments Ltd., Lymington, U.K.). As previously described, the air canopy system uses filtered air to flow over the operator beneath the plenum. The same filter remained in the dust-laden entry air during all testing. To ensure the filter continued to remove dust from the supply air, an isokinetic orifice, connected to a gravimetric sampler, was placed in the tubing that supplies air to the plenum. The air supply was monitored throughout five hours of testing (in one air velocity test) to ensure that the airflow from the plenum was uncontaminated. After a total of five hours of testing, the concentration of dust in the filtered air was 0.035 mg/m^3.

Figure 12 shows the sampler locations relative to the velocity contours. There is a distinct drop in velocity at the transition zone between the square and trapezoidal areas of the perforated plate. Samplers D and E were located in this area to measure dust concentrations. The dust measurements verified that this area provided less protection than the areas where the other samplers were located. For instance, for the test velocity of 0.61 m/s (120 fpm), the dust levels from samplers D and E were 4.5 times greater than those measured at samplers A through C. The authors believe this low-flow area was created partially by the metal seam in the perforated plate. Another cause may be the transition zone inside the plenum from the square to the trapezoidal region.

Data analysis

Dust concentrations in the entry were compared to the dust levels measured under the plenum for all three velocities. For comparative purposes of this part of the analysis, the six samplers under the plenum were analyzed collectively, based on the fact that the operators are constantly moving under the entire area of the canopy throughout the drilling cycle. Dust concentrations measured beneath the plenum were averaged and compared to the two average concentrations measured on the entry samplers. Table 1 shows data collected from the 0.3 m/s (60 fpm) velocity test.

Figure 13 shows a graph of the average concentrations from the six test replications for the 0.3 m/s (60 fpm) velocity test from Table 1. To illustrate the degree of uncertainty between the tests, the graph is shown with standard error bars (standard error of the mean). As can be seen on the graph, the tests have low standard deviations from the mean in the entry measurements and higher variability under the plenum. The higher variability under the plenum is a result of the higher dust measurements at samplers D and E. The

Table 2

Six-test average of all tested velocities.

	Six-test average concentration, mg/m³		
Velocity m/s (fpm)	Under plenum	Entry (outside plenum)	Reduction, %
0.05 (10)	1.95	6.90	72
0.03 (60)	1.68	5.01	67
0.61 (120)	1.50	6.07	75

Figure 14

Dust concentration averages for three test velocities showing standard error bars.

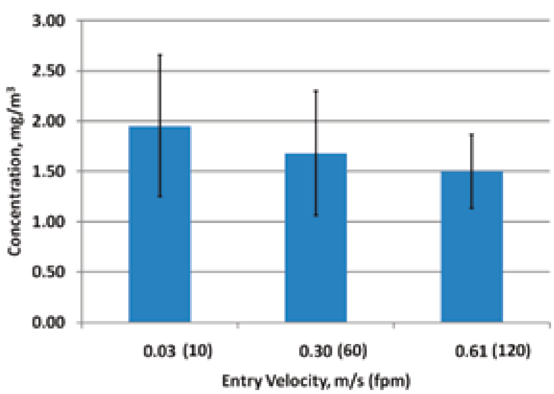


Figure 15

NIOSH-designed air canopy system on a roof bolter in an underground coal mine.

graph also visually shows a distinct difference in average dust concentrations at the plenum and entry sampling locations.

A test for significance at 95% confidence using a statistical *t*-test was also performed on the two sampling locations. The *t*-test shows that there is a significant difference ($p < 0.05$) between measurements taken in the entry and measurements taken under the plenum. A 67% reduction in dust concentration is shown under the plenum at this test velocity. This graph and the tests for confidence are representative of all three test velocity results when comparing dust concentrations under the plenum versus outside the plenum.

The data were also summarized to show dust concentration comparisons at each of the test velocities. The measured dust levels under and outside the plenum at the different test velocities are shown with associated dust reductions in Table 2. Statistical *t*-tests show that a significant difference in dust concentration is measured for each test velocity when comparing levels under the plenum and in the entry. Figure 14 shows the three average dust concentrations (1.5 to 1.95 mg/m³) under the plenum at each velocity. Although dust reduction appears to be greater as entry velocity increases, the chart, shown with standard error bars from the six test measurements at each velocity, implies no significant difference related to change of velocity. Dust reductions were similar for all test velocities, and, therefore, the system is effective for reducing respirable dust concentrations for velocities common to roof bolting work areas.

Field testing

Field testing of the canopy air curtain system was attempted on two occasions to verify results obtained in the laboratory (Fig. 15). For each field test, the system was delivered to the mine site in advance for installation on the roof bolting machine. However, due to operational problems (fan seal damage) while integrating the centrifugal fan into the hydraulic system of the roof bolter, both of these studies ended prematurely and provided limited data for analysis. Despite the problems encountered, the studies were beneficial in that they identified the need for a dedicated hydraulic stage on the roof bolter to independently operate and regulate the fan speed. The machine manufacturer has since added additional hydraulics on the roof bolter to test another air canopy design.

Although no significant results can be discerned from the limited field data, the two places that were sampled showed improvement under the plenum. Table 3 shows the two roof bolter places that were measured before damage to the fan occurred. These data were measured using Personal Dust Monitors (PDMs) (Thermo Fisher) worn by the roof bolter operators on either side of the dual boom machine. Time studies were conducted during the sampling, and it was found that during the bolting cycle (from tram in to tram out of a place) the operator is under the canopy about 66% of the time. From the few roof bolter places that were sampled, reductions in respirable dust were evident.

The concentrations measured by PDMs worn by the operators during the entire sampling period (194 min) were compared and found to be 2.93 mg/m³ for the operator under the plenum and 4.46 mg/m³ for the operator under the unmodified canopy, a reduction of 34% when using the canopy air curtain.

Conclusion

Previous contract work and research studies have shown that air curtains can effectively provide protective zones of clean air in dusty mine environments. To successfully adapt this technology to a roof bolting machine, the air curtain plenum had to be modified to conform to the roof bolting

Table 3

Respirable dust concentrations and reductions from field data.

Bolter workplace	Operator under plenum, mg/m^3	Operator under unmodified canopy, mg/m^3	Reduction, %	Velocity at bolter
1	1.81	3.88	53	Negligible*
2	4.73	7.3	35	Negligible*

*Not able to be detected on a vane anemometer.

Figure 16

Alternative designed air curtain based on mine/manufacturer collaboration.

machine's canopy, in order to provide greater airflow coverage. However, this modification changed the airflow patterns, resulting in an uneven flow of air beneath the plenum. Through CFD simulation and trial-and-error testing, a unit was developed to provide filtered air under approximately 70% of the canopy. Laboratory tests revealed that air velocity exiting the plenum in excess of 0.51 m/s (100 fpm), 25.4 cm (10 in.) below the unit, will provide an area of reduced dust exposure to operators in entry air velocity of up to 0.61 m/s (120 fpm). Statistical analysis of laboratory data show that, at each test velocity, a significant reduction in respirable dust was achieved under the plenum. Reductions of 72%, 67% and 75% were realized for 0.05, 0.3 and 0.61 m/s (10, 60 and 120 fpm), respectively.

Field testing of the system, while incomplete, showed that the air curtain can be successfully integrated into the canopies of roof bolting machines and that these machines can be modified and retrofitted with blower fans, filters and hydraulics. The limited field data that was available for analyses revealed reduced operator dust exposures. However, further field testing should be conducted.

An equipment manufacturer is currently working with a mining company in Virginia to add air curtains on the mining company's roof bolter canopies (Fig. 16). Another company in Kentucky is retrofitting the cabs of its shuttle cars with air curtains to reduce operator dust exposure in blowing curtain ventilation schemes. Recent and continued advances in CFD modeling may result in improved air curtain designs for use on mining equipment.

Disclaimer

Mention of any company or product does not constitute endorsement by the National Institute for Occupational Safety and Health. The findings and conclusions in this paper are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health.

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