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A field study of a roof bolter canopy air curtain (2nd generation) for respirable coal mine dust control

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Abstract

A 2nd generation roof bolter canopy air curtain (CAC) design was tested by National Institute for Occupational Safety and Health (NIOSH) at a Midwestern underground coal mine. During the study, the roof bolter never operated downwind of the continuous miner. Using a combination of personal Data Rams (pDR) and gravimetric samplers, the dust control efficiency of the roof bolter CAC was ascertained. Performance evaluation was determined using three methods: (1) comparing roof bolter operator concentrations underneath the CAC to roof bolter concentrations outside the CAC, (2) comparing roof bolter operator concentrations underneath the CAC to the concentrations at the rear of the bolter, and finally, (3) using the gravimetric data directly underneath the CAC to correct roof bolter operator concentrations underneath the CAC and comparing them to the concentrations at the rear of the bolter. Method 1 dust control efficiencies ranged from −53.9% to 60.4%. Method 2 efficiencies ranged from −150.5% to 52.2%, and Method 3 efficiencies ranged from 40.7% to 91%. Reasons for negative and low dust control efficiencies are provided in this paper and include: incorrect sampling locations, large distance between CAC and operator, and contamination of intake air from line curtain. Low dust concentrations encountered during the testing made it difficult to discern whether differences in concentrations were due to the CAC or due to variances inherent in experimental dust measurement. However, the analyses, especially the Method 3 analysis, show that the CAC can be an effective dust control device.

Keywords

Coal; Roof bolter; Respirable dust; Underground mining

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7. Disclaimer

The findings and conclusions in this manuscript are those of the authors and do not necessarily represent the views of the National Institute for Occupational Safety and Health (NIOSH). Mention of company names or products does not constitute endorsement by NIOSH.

1. Introduction

Canopy air curtains (CAC) were originally developed for use on the cabs of continuous miners to protect miners from underground coalmine respirable dust in the mid-1970s by the U.S. Bureau of Mines (USBM). Once developed, field testing continuous miners at different underground coal mine sites demonstrated CAC dust control efficiencies ranging from 23% to 69% [1]. In the 1980s, the National Coal Board modified the USBM CAC and field tested it on a boom-type heading machine. Results of their testing demonstrated dust control efficiencies of 35–68% in blowing ventilation and 40–87% in exhausting ventilation [2]. This field testing demonstrated the ability of the CAC to successfully protect miners from respirable coal mine dust.

The elimination of the cab on continuous miners occasioned the development for roof bolter operators. Laboratory testing of the roof bolter CAC has shown that the CAC can be an effective respirable coal mine dust control for roof bolter operators. Laboratory test results demonstrated dust control efficiencies ranging from 14% up to 75% [3–5]. Unfortunately, there is limited information on their effectiveness for controlling respirable coal mine dust in actual operating conditions at underground coal mining sites. Two underground tests of the CAC on roof bolters demonstrated dust control efficiencies of 35% and 53% before problems occurred with operation of the CAC [4]. This study is the first to conduct field testing of the roof bolter CAC of sufficient duration to collect an adequate amount of data allowing analysis to demonstrate its effectiveness for roof bolter operators.

Very few studies of CAC have been completed outside of the USBM and NIOSH. A radial air curtain has been developed by the College of Mining and Safety Engineering at Shandong University of Science and Technology and is fully described in a Computational Fluid Dynamic (CFD) study of the device [6–8]. However, this device is radically different and is not a CAC which provides personal protection to an individual mine equipment operator. This device is a tube that attaches to the blowing ventilation tubing and consists of slots to allow air to radially emanate from the device. It provides airflow that creates a wall of air that essentially traps dust between the airwall and the face, protecting machinery operators who maybe outby the airwall. An exhaust ventilation tubing is required to remove the trapped dust at the face. These studies focused on the CFD analysis of the airflows showing its effectiveness. Field studies were conducted to show their curtain performance. However, there was minimal discussion of its effectiveness for personal protection. While the device provided protection to mine equipment operators using airflow, the methodology of protection is very different from that of the CAC. Another version of an air curtain was designed to be installed on a longwall shearer body. This curtain created a wall of air which separated the ventilation airflow into two channels. One kept dust contaminated air at the face while the other kept the clean air in the walkway. CFD analysis and field measurement comparisons were conducted to show its effectiveness [9]. While effective, this methodology is also different from the CAC.

Since the implementation of the new respirable coal mine dust limit from 2.0 to 1.5 mg/m^3, roof bolter CACs are becoming more commonplace in underground coal mines as a dust control tool to prevent roof bolter operator overexposure to respirable coal mine dust [10].

J.H. Fletcher & Co. has been instrumental in delivering an effective design which incorporates the filter, blower, and canopy plenum seamlessly into the design of the roof bolter, resulting in a successful operational roof bolter CAC.

A field study was conducted by the NIOSH to test the effectiveness of the roof bolter CAC for respirable coal mine dust control. The study was conducted at Prairie State Energy's underground coal mine; the Lively Grove Mine. The Lively Grove Mine is a room-and-pillar mine containing coal from the Herrin #6 seam. The mine produces approximately 7 million tons of coal per year to the adjacently located power plant. Testing was conducted on a roof bolter which operated in entries 7–13 in a 13-entry main. The roof bolter is manufactured by J.H. Fletcher & Co. and is listed as serial #: 2015–306. The mine employed a blowing face ventilation system to the roof bolter machine during bolting operations. However, during this testing the roof bolter never operated down wind of the continuous miner.

The CAC system is integrated into the roof bolter machine with the hydraulically driven fans and filter mounted on the roof bolter body and the plenum, which provides air over the operator, incorporated into the roof bolter canopy. The fans are connected to the canopy via 10.2-cm diameter hose. The left and right side of the roof bolter each had a CAC system in-place, which operated the entire time during roof bolter operation.

The shape of the canopy/plenum used at the mine site is shown in Fig. 1. This canopy is the 2nd generation design from J.H. Fletcher's original slotted CAC. The original slotted CAC had dust control efficiencies ranging from 14.2% to 24.5% in the laboratory [5]. This 2nd generation CAC is an improvement upon NIOSH's original design that uses uniform airflow across the plenum. The uniform filtered airflow provides protection to the roof bolter operator by flowing directly over the operator resulting in displacement of air contaminated by respirable dust from the operator's breathing zone. The uniform filtered airflow also provides a column of air that prevents any entry ventilation airflow contaminated with respirable coal mine dust from penetrating. The 2nd generation CAC also, implements recommendations from the NIOSH computational fluid dynamics (CFD) evaluation conducted on the original design which recommended staggered slots or nozzles if perimeter outlets are to be used [5]. This new design incorporates staggered perimeter nozzles to prevent infiltration of contaminated air into the CAC domain or the protection zone. The protection zone consists of an equally spaced pattern of holes providing airflow over the roof bolter operator at a lower velocity than the perimeter holes.

2. Sampling method

Gravimetric and instantaneous samplers were used to test the CAC for respirable dust control. The gravimetric sampler is the coal mine dust sampling unit consisting of an ELF Escort pump operating at 2.0 L/min, a 10-mm Dorr-Oliver cyclone, and a 37-mm, 5-μm PVC filter. The gravimetric sampler is the coal mine dust personal sampler unit (CMDPSU) that was used to sample coal mine respirable dust prior to February 1, 2016 [11]. It is still used for respirable silica dust sampling due to the need to conduct silica analysis on the sample collected on the 37-mm filter. This sampling method only provides a time-weighted-average (TWA) dust concentration for the time period sampled. To calculate the dust concentration from the CMDPSU the filters are pre-and postweighed in a controlled environment to obtain the sample mass on the filter. Then, the concentrations are calculated using the following Eq. (1).

$$\text{Conc.} = (\text{Mass} \times 1000)/(\text{Flowrate} \times \text{Sampletime}) \tag{1}$$

where Conc. is the respirable dust concentration, mg/m^3; Mass is the mass of sample on 37-mm filter, mg; Flowrate is the flowrate of air through the ELF Escort pump, generally set to 2.0 L/min; and Sample time is the length of sampling period, min.

The instantaneous sampler was the Thermo Fisher Scientific pDR-1000. This instantaneous sampler uses light-scattering technology to measure dust in the range ≤10 μm and has the capability to record dust measurements. It is Mine Safety and Health Administration (MSHA) approved for intrinsic safety, but it is not an MSHA-approved compliance sampling device under Title 30 Part 74 of the Code of Federal Regulations [12]. This sampler is used by NIOSH for research purposes because it allows instantaneous dust sampling at user-defined time intervals. In order to analyze the data among different pDR-1000s used in this study, the data from the pDR-1000 must be calibrated to obtain corrected data. Calibration is accomplished using a gravimetric sampler along with the light-scattering instrument. The calibration ratio is calculated using the following Eq. (2):

$$\text{Ratio} = \text{Grav}/\text{Instant} \tag{2}$$

where *Ratio* is the calibration ratio; *Grav* is the gravimetric TWA concentration, mg/m^3; and *Instant* is the instantaneous optical TWA concentration from the pDR-1000, mg/m^3.

Next, the calibration ratio is multiplied by each instantaneous optical concentration recorded by the pDR-1000 in order to obtain absolute concentrations. Calibration is required due to the different particle characteristics encountered in the field and allows for correction of dust measurement variations due to these characteristics [13].

Sampling packages comprised of two gravimetric samplers and one instantaneous sampler was used to sample respirable dust at different locations in the section (Fig. 2). Fig. 3 shows the locations of the sampling packages.

As shown in Fig. 2, the pDR-1000 is in the middle of the rack with the gravimetric samplers located adjacently on each side of the pDR-1000.

Intake samplers (blue[1]) were located at the entrance of the line curtain into the roof bolting and continuous miner sections. Return samplers (red) were located in the return of the roof bolting and continuous miner section. The roof bolter was outfitted with sampling packages (purple) at the front, mid-section (just behind the canopy), and rear of the center of the roof bolter. The sampling packages were located so they did not interfere with the operators' activities. Additionally, each operator was outfitted with a sampling package (green) consisting of one pDR-1000 and two gravimetric samplers implemented into a wearable

[1]For interpretation of color in Fig. 2, the reader is referred to the web version of this article.

vest. The gravimetric cyclones' inlets were placed at both the right and left lapels. The pDR-1000 was placed in a vest pocket on the operator's back. This setup allowed determination of potential exposures to the roof bolter operator.

Also, two additional gravimetric cyclone inlets with filters were placed directly underneath the plenum outflow on each side of the roof bolter machine. The ELF Escort pumps operating at 2.0 L/min were mounted to the roof bolter mast. These samplers were used to monitor the respirable dust concentrations directly underneath the CAC. The sampler cyclones were positioned so that the inlet openings were oriented pointing downward. Once these samplers were started, they were not stopped until the cyclone was repositioned upright.

3. Testing

Face ventilation readings were measured and recorded for each cut at each continuous miner and roof bolter location (Table 1). The roof bolter operators were allowed to complete their tasks as they normally would. Time studies were conducted for the continuous miner and roof bolter machines. The purpose of the time study for the continuous miner was to document when the continuous miner was operating while noting the location of the miner with respect to the roof bolter. During the study, the roof bolter never operated downwind of the continuous miner. Therefore, data collected at the continuous miner locations was not analyzed. The time study for the roof bolter was conducted to monitor the location of the bolter operator with respect to the canopy and to record roof bolter operational times. This data has been analyzed to determine potential exposures to the roof bolter operators and to calculate the canopy air curtain field efficiency.

4. Results

The gravimetric TWA respirable dust concentrations are reported in Table 2, showing that the respirable dust concentrations measured at the site were very low. This shows the concentrations during the entire time for each day at the study site. Table 3 presents the TWA respirable dust concentrations measured underneath the roof bolter canopies and the personal samples measured for both roof bolter operators. The bolter operators did have some of the higher TWA concentrations encountered during the study. However, these concentrations were very low ranging from 0.112 to 0.232 mg/m^3. The gravimetric concentrations for the roof bolter operators include the time underneath the canopy air curtain as well as the time outside the canopy's zone of protection. For comparison purposes, Table 4 presents the TWA respirable dust concentrations measured at the intake and return to the continuous miner location. The amounts of dust generated by the continuous miner were at very low concentrations.

Testing was conducted over three days to evaluate the CAC effectiveness. Testing was limited the first day due to mechanical problems with the roof bolter. During roof bolter operation, the canopy air curtain was operated constantly. Table 5 presents the velocities in m/s that were measured underneath the canopy air curtain. Measurements were not taken on the first day due to the roof bolter maintenance problems. On the second day (April 20th) it was noticed that the air hose to the right side canopy was kinked and had holes through which air leaked. The hose to the left side canopy was also kinked, but no leaks were observed. The holes on the right side canopy were fixed prior to the measurement of the canopy airflow velocities on the second day. But the right side canopy still had a much lower flowrate than the left side (Table 5). It is not known what caused this, possibly the right hose was kinked so much that it restricted airflow. On April 21, the airflows to the canopy were similar.

In order to analyze the performance of the canopy air curtain for respirable dust control effectiveness, there are three approaches that can be used for comparison. All approaches analyze corrected pDR data to calculate the concentrations. The first approach (Method 1) is to compare the personal samples of the bolter operators in two categories—concentration underneath the canopy and concentration outside of the canopy. The resulting concentrations were calculated using data from the pDR-1000 that the operator wore, calibrating the data using the gravimetric samplers worn by the operator. Then, the pDR-1000 data was segregated to time underneath the CAC and time outside the CAC. This resulted in concentrations for each operator underneath and outside the CAC, which can potentially be used to determine the control efficiency of the canopy air curtain.

However, monitoring of the operators when working outside of the CAC was not conducted. During these instances, the operators could have been working in more dusty airflow or they may have spent more time located in a cleaner airflow (intake air), which would have resulted in the negative dust control efficiencies. Additionally, the tasks completed while outside the CAC, while undocumented, were different from the tasks completed while working underneath the CAC. The tasks while working underneath the CAC were related to operating the roof bolter machine, whereas tasks outside of the CAC were not. Examples of outside CAC tasks were hanging ventilation curtain, loading supplies on roof bolter, hanging roof bolter power cable, tramming roof bolter machine, etc. For this reason, the dust control efficiencies that were calculated using Method 1, comparisons of the roof bolter operator underneath the canopy to the roof bolter operator outside the canopy, probably should not be used to establish the respirable dust control efficiency of the CAC. Tables 6–11 present the results from Method 1.

Another method (Method 2) of analyzing the performance of the canopy air curtain is to compare the personal samples of the bolter operators when working underneath the canopy with the area samples taken at the rear of the bolter. Again, the concentrations for the operator working underneath the CAC were calculated from the corrected pDR-1000 data using the times the operator was underneath the CAC. The concentrations for the area samples at the rear of the bolter were calculated from corrected pDR-1000 data using only the time that the operator worked underneath the canopy. These rear pDR-1000 concentrations were corrected by calibrating these with the gravimetric samplers on the rear of the bolter.

The rear of the bolter was used instead of the return sampler as the return sampler may have been inappropriately placed during testing. The return sampler was often placed at the roof just around the corner outside of the roof bolting entry in the immediate crosscut. This sampler would be impacted by different ventilation flows and activities in the cross-cut than what was occurring in the roof bolting entry. In retrospect, the return sampler should have been placed in the center of the entry to effectively measure respirable coal mine dust from the roof bolting activities.

The rear of the bolter sampler was the sampler that was closest to being in the center of the entry. Therefore, it was thought to be recording respirable coal mine dust levels that were most representative of those in the entry. The rear of the bolter sampler was also used over the bolter mid samplers, because the bolter mid sampler ended up between an opening underneath the tray that holds the bolting materials (roof bolts, mesh, plates, etc.) and the roof bolter body. This placement in effect removed the bolter mid samplers from any airflow movement, which is the reason for such low concentrations recorded at the bolter middle sampling location.

However, the use of the rear bolter sampler as a comparison may be limited due to the increased distance between the dust source (drilling) and the samplers. The dust concentrations at the rear of the machine samplers may have lower dust levels than at the operators who are closer to the dust source due to the ventilation effects of additional dilution and mixing of the respirable dust. This circumstance could be a potential cause of negative dust control efficiencies. Therefore, using evaluation Method 2, while acceptable, may not be accurate because of the circumstance of these differing locations of the samplers, underneath the CAC and at the rear of the bolter. It would be desirable to have both samplers in the same approximate locations. Tables 12–17 show the results of Method 2.

Method 3, the final method, used the gravimetric samplers that were placed directly underneath the CAC to calibrate the pDR-1000 used for the operator personal samplers. This compares the under CAC samplers to the rear of the bolter samplers. Comparison was completed using only the time the operator was underneath the CAC. These concentrations potentially show the maximum dust reduction possible. Tables 18–23 show the results of Method 3.

5. Discussion of results

As stated previously, the gravimetric respirable dust concentrations measured during the field study were very low (<0.500 mg/ m^3). Low concentrations can make it difficult to discern the cause of the differences between the concentration data sets; whether the cause is due to the dust control device or due to variances inherent in experimental dust measurement. Concentrations measured using the CMDPSU can be subject to uncertainty due to random weighing errors of the 37-mm filters. This uncertainty can have a significantly large effect on filter weighing when low mass (<0.100 mg) of sample is collected on the 37-mm filters, which corresponds to low concentrations [14,15]. During this field study 72 respirable dust samples were collected on 37-mm filters, with 51 containing mass less than 0.100 mg, showing that there could be a high degree of uncertainty in the TWA respirable dust concentrations.

The roof bolter intake concentrations ranged from 0.035 to 0.200 mg/m^3, while the other sampler location concentrations around the roof bolter ranged from 0.056 to 0.188 mg/m^3 (Table 2). Generally, the intake concentrations of the roof bolter were lower than the return concentrations, except for day 3 of the study. The day 3 exception was probably due to bolting in crosscuts where high ventilation airflow quantities were encountered. The highest respirable dust concentrations encountered were at the continuous miner return, ranging from 0.330 to 0.417 mg/m^3 (Table 4). Even these higher respirable dust concentrations were generally low compared to respirable dust concentrations measured in continuous miner returns at other mine sites [16,17]. However, the continuous miner did not operate upwind of the bolter during this study.

In the evaluation of the data shown in Tables 6–23, statistical analysis was conducted on the data using the Wilcoxon-Mann-Whitney test for two independent variables. This statistical test is a nonparametric test used to determine if the averages of the datasets differ. Nonparametric tests are used when the data are not assumed to have a normal distribution [18]. However, this does not preclude the test from being used when the data exhibits a normal distribution. This test ranks the data from smallest to largest, and then uses the sum of the rankings to determine whether the averages of the two datasets differ. In these analyses, $\alpha = 0.05$, which represents the significance level of the test.

In comparing the datasets using Method 1, the roof bolter operator underneath the canopy to the roof bolter operator outside the canopy (Tables 6–11), the April 19th control efficiency of 60.4% in entry 8 for the left side bolter (Table 7) was statistically significant (95% confidence). The datasets used to calculate the other dust control efficiencies for the day were not found to be statistically different, even though they exhibited positive dust control efficiencies. April 20th (Tables 8 and 9) also had only one instance of a dust control efficiency being statistically significant with 21.2% dust control efficiency for the left side bolter in entry 7. On April 21st, there were three instances of dust control efficiencies being statistically significant (Tables 10 and 11): –48.7% dust control efficiency for the right side bolter in entry 7, –53.9% dust control efficiency for the left side bolter in crosscut 9 left, and 26.3% dust control efficiency for the left side bolter in crosscut 8 left. Negative dust control efficiencies indicate an increase in dust exposure. However, due to reasons stated previously, Method 1 probably should not be used to the dust control efficiency of the CAC.

Comparison of the datasets using Method 2 (Tables 12–17), roof bolter operator underneath the canopy to the rear of the roof bolting machine, were completed. For April 19th, control efficiencies of –101.3% for the right side bolter in entry 8 and –135.2% for the left side bolter in entry 8 were statistically significant (95% confidence) as shown in Tables 12 and 13. On April 20th (Tables 14 and 15), none of the dust control efficiencies were statistically significant, meaning that the datasets used to calculate the dust control efficiencies were not statistically different from each other. On April 21st, two of the right side roof bolter operator's dust control efficiencies were statistically significant; 15.8% dust control efficiency in crosscut 9 left, and 52.2% dust control efficiency in crosscut 8 left. The left side bolter dust control efficiencies were statistically significant for three places: −150.5% dust control efficiency in entry 7, –40.0% dust control efficiency in crosscut 9 left, and –4.6%

dust control efficiency in crosscut 8 left. These results from Method 2 could be inaccurate due to the previously mentioned dilution effect.

The comparison of the datasets using Method 3, the roof bolter operator underneath the canopy pDR-1000 sampler calibrated to the corresponding underside CAC plenum gravimetric with the rear of the bolter location (Tables 18–23), was conducted to show the potential maximum dust control efficiencies. For April 19th (Tables 18 and 19), all dust control efficiencies calculated were not statistically significant, meaning that the datasets used to calculate the dust control efficiencies were not statistically different. During April 20th, the left side roof bolter had dust control efficiencies ranging from 70% to 91% (Table 20) and the right side roof bolter dust control efficiencies ranged from 77% to 83% (Table 21). All dust control efficiencies calculated for April 20th were statistically significant. On April 21st, three of the right side roof bolter dust control efficiencies were statistically significant: 63.6% dust control efficiency in entry 7, 62.3% dust control efficiency in crosscut 9 left, and 78.6% dust control efficiency in crosscut 8 left (Table 22). The left side bolter dust control efficiency was also statistically significant for three places: 40.7% dust control efficiency in crosscut 9 left, 89.1% dust control efficiency in entry 9, and 58.2% dust control efficiency in crosscut 8 left (Table 23).

The dust control efficiencies were variable, ranging from 40% to 91%. While these dust control efficiencies represent the maximum possible efficiencies, it is noted that the lower efficiencies were located in crosscuts where the ventilation airflows were high. Past laboratory research has shown that higher interference or ventilation airflows can have a negative impact on CAC performance[19–21].

On numerous occasions dust exposures increased while using the CAC resulting in negative dust control efficiencies. There are several possible explanations for the cause of these negative dust control efficiencies:

(1) The gravimetric dust concentrations encountered during this study were low (≤0.232 mg/m^3 for the roof bolter and ≤0.417 mg/m^3 for the continuous miner areas). When the dust concentrations are low, it is more difficult to clean the air with dust control devices that use airflow to prevent exposure to the contaminated air. Because these airflows could potentially re-entrain dust into the air at concentrations equivalent or slightly more than those the device is trying to reduce. The low dust concentrations from the study could be a major contributor to the cause of the negative dust control reductions encountered.

(2) The pDR was located on the back of the operator while the gravimetric samplers were located at the operator’s lapel locations (Fig. 4). When operating the roof bolter machine installing roof bolts, it was observed numerous times that the operator’s back moved out of the downward airflow stream into contaminated air, while the gravimetric samplers were located within the canopy’s airstream. The same could be said of the gravimetric samplers being outside the canopy airstream while the pDR was located within the air-stream. These occurrences were not recorded because it was not thought to be an issue during the actual data recording of the field study. A solution to these occurrences is to locate the samplers, both the pDR and gravimetric, in the same general location at the front of the operator. Another possible solution is to create a larger canopy plenum footprint, which allows the operator to work within the airstream without moving in and out of the airflow.

(3) While conducting the field study the operators were monitored during the times spent underneath the CAC while bolting. However, when the bolting task was complete, the operators continued to wear the samplers while working outside of the CAC. However, monitoring of the operators when working outside of the CAC was not conducted. During these instances, the operators would have been working completing different tasks from roof bolter machine operation when underneath the CAC. Additionally, they may have spent more time located in a cleaner airflow (intake air), which would have resulted in the negative dust control efficiencies.

(4) Researchers noticed many times that there were large distances between the bottom of the CAC plenum and the top of the roof bolter operator's hardhat. This translated to the sampling locations on the operator being much further away from the plenum than the 25.4 cm distance underneath the canopy tested in the laboratory, which represented the distance from the plenum to the worker's breathing zone [4]. Many of the distances between plenum and the top of the roof bolter operator's hard hat were estimated to be 50.8–76.2 cm. Additionally, there was movement of the operator into more turbulent airflow zones. When sampling in the laboratory, the dust control efficiencies of the CAC at distances > 25.4 cm were much lower. For lower sampling locations at 76.2 cm below the plenum, the dust control efficiencies ranged from 14% to 19% with the original slotted canopy compared to 17–25% at 25.4 cm [5]. This shows that lower dust control efficiencies are encountered when the operator is further away from the airflow exiting the plenum. This is due to the turbulent airflow at lower locations, allowing contaminated air to infiltrate the airstream. Unfortunately, the canopy position over the operator was not monitored closely for this study. Positioning of the canopy could contribute to negative dust control efficiencies especially when the canopy is 50.8 cm or more above the operator.

(5) Another possible cause of the negative dust control efficiencies is contaminated intake air to the roof bolter machine entry using a line curtain. It was observed that the line curtain was contaminated with coal and rock material from prior use. The placement of this "dirty" or contaminated line curtain could have resulted in the intake airflow re- entraining dust from the curtain and contributing to higher exposures to the operators. Because the intake samplers were placed at the entrance to the line curtain and not the exit, there was no way to measure the dust from any re-entrainment from the line curtain. This is especially possible for the left side operator who typically places the line curtain on the left side of the roof bolter machine.

6. Conclusions

The results of Method 1, comparing roof bolter operator's concentrations underneath the CAC to roof bolter operator's concentrations outside of the CAC, show that dust control efficiencies ranged from −54% to 60%. When comparing Method 2, the roof bolter operator's concentrations underneath the CAC to the concentrations at the rear of the roof bolter, the dust control efficiencies ranged from –150% to 52%. The negative dust control efficiencies show an increase in dust exposure while working underneath the CAC, and are primarily caused by the result of the incorrect location of the pDR in relation to the gravimetric samplers. Method 1 evaluation may not be an acceptable evaluation because of the fact that roof bolter tasks while outside the CAC were undocumented and differed from the tasks completed while underneath the CAC. Method 2 evaluation may not be accurate due to the dilution effect of measuring the respirable dust at the rear of the roof bolter. However, the 50.8–76.2-cm distance between the roof bolter plenum and the top of the roof bolter hardhat, and the intake air contamination from the line curtain also contributed to dust control efficiency results that were lower, and possibly resulting in negative dust control efficiencies. Additionally, the concentrations encountered were very low, which means the CAC may not need to be operated when dust concentrations throughout the mine are very low as they were in this field study.

Finally, when comparing Method 3, the roof bolter underside sampler's concentrations underneath the CAC to the concentrations at the rear of the roof bolter samplers, the dust control efficiencies ranged from 40% to 91%. These dust control efficiencies could represent the maximum possible dust control efficiencies provided to the roof bolter operator that were encountered during testing. These control efficiencies would also be impacted by the previously mentioned issues. However, they are also more representative of the dust control efficiencies the roof bolter would encounter as long as the operator remained in the protection zone of the CAC. These efficiencies demonstrate that the roof bolter CAC can be an effective dust control tool.

It should be noted that the amount of time the roof bolter operators were underneath the CAC ranged from 7 to 46 min per bolting location. During this study overall, the time roof bolter operators spent underneath the canopy was on April 19th 43 min out of 237 min (≈18% of the time), on April 20th 104 min out of 316 min (≈33% of the time), and on April 21st 159 min out of 321 min (≈50% of the time). The time underneath the canopy for April 19th was much lower than other days due to the maintenance required on the roof bolter machine. This shows that the protection is provided for only a short time during the shift and only when roof bolting underneath the CAC.

In a previous study, limited field study data showed that the NIOSH-designed CAC provided dust control efficiencies of 35% and 53% [4]. Discussions with the authors reported that the sampler used was the 3600 personal dust monitor (PDM) with the sample inlet located on the cap lamp at the top of the hardhat. The dust control efficiencies from the Listak study could be comparable to the results of the dust control efficiencies evaluating the CAC underside sampler's concentrations with the concentrations at the rear of the roof bolter samplers, which ranged from 40% to 91%. This demonstrates that the CAC design utilized for this study with perimeter nozzles and uniform plenum airflow shows promise in providing protection from respirable coal mine dust to the roof bolter operator.

It is recommended that additional studies be completed and consider the following conditions:

(1) When sampling with the wearable vest, the pDR should be placed near the gravimetric inlets. This will keep both sampling devices in the same vicinity when the roof bolter operator is moving around at his station.

(2) Place a sampling package outside the CAC protection zones near the middle area between the two roof bolter operators, and locate it such that it will be able to sample the surrounding airflow outside the CAC zones.

(3) Investigate using the PDM (The PDM is the continuous personal dust monitor that is MSHA approved for compliance respirable dust sampling under Title 30 Part 74 of the Code of Federal Regulations) as a sampling device instead of gravimetric samplers. It would be more desirable to conduct the sampling with a PDM in conjunction with a pDR. This would reduce the number of sampling devices that the operator would wear and thus reduce the number of sampling ports or inlets. Sampling ports would still need to be located together in the same vicinity. Sampling using the PDM and pDR would eliminate the need for the operators to wear sampling vests during bolting operations.

(4) Sample more conditions when the roof bolter machine is downwind of the continuous miner to sample the effectiveness of the CAC under higher dust concentrations. Conducting the test in higher dust concentrations would eliminate the problems encountered with the low dust concentrations.

Conducting additional roof bolter CAC studies will help verify that the CAC is an effective dust control device to protect roof bolter operators from coal mine respirable dust exposure.

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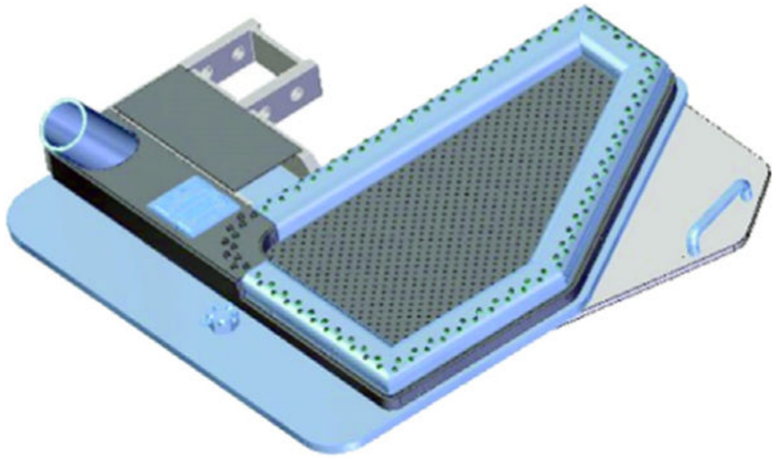

Fig. 1.
Roof bolter canopy with the canopy air curtain plenum built in.

Fig. 2.
A typical sampling package consisting of a pDR-1000 and two gravimetric samplers used by NIOSH.

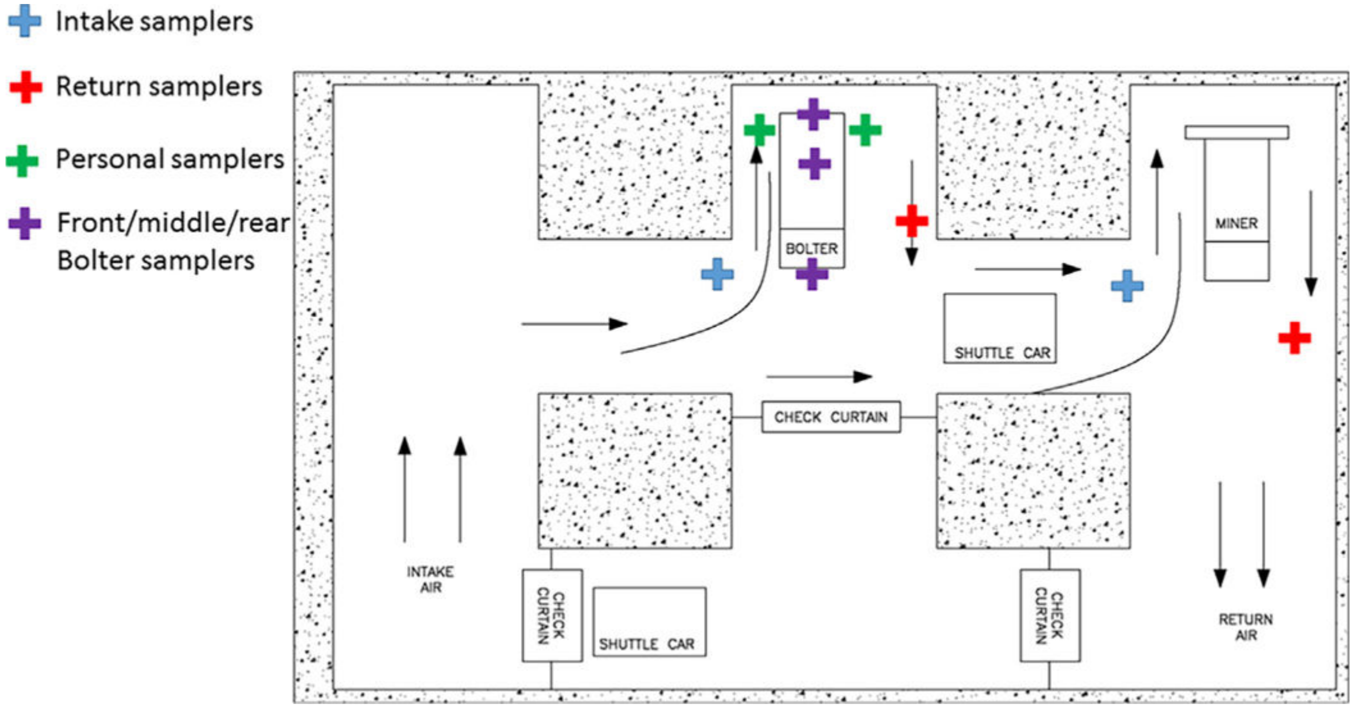

Fig. 3.
Locations of sampling packages for testing the dust control efficiency of the roof bolter canopy air curtain.

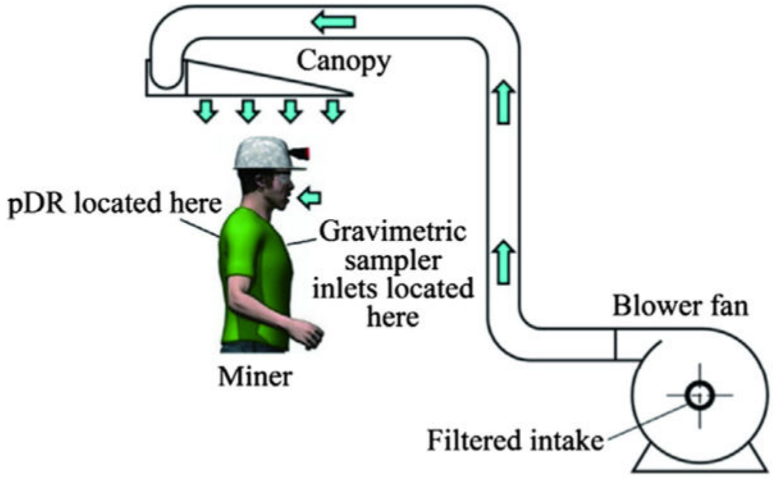

Fig. 4.
Locations of gravimetric sampler inlets and pDR sampler with respect to the roof bolter operator.

Table 1

Face ventilation data of roof bolter machine entries.

Date	Entry #	Height (cm)	Width (cm)	Curtain offset (cm)	Velocity (m/s)	Airflow quantity (m^3/s)
19-Apr-17	8	213	NR	152	1.52	4.96
19-Apr-17	7	208	NR	109	1.28	2.90
20-Apr-17	7	196	NR	152	1.44	4.30
20-Apr-17	8	196	NR	168	0.94	3.07
20-Apr-17	9	224	NR	213	0.49	2.33
21-Apr-17	7	206	NR	123	115	2.88
21-Apr-17	9 right	213	521	NC	0.73	8.08
21-Apr-17	9 left	213	521	NC	0.73	8.08
21-Apr-17	9	208	NR	203	0.70	2.95
21-Apr-17	8 left	229	NR	287	1.12	7.37

Notes: NC means no curtain, and NR means not recorded.

Table 2

Gravimetric time-weighted-average respirable dust concentrations for the roof bolter section.

Date	Intake concentration (mg/m^3)	Bolter front concentration (mg/m^3)	Bolter mid concentration (mg/m^3)	Bolter rear concentration (mg/m^3)	Return concentration (mg/m^3)	Time (min)
19-Apr-16	0.124	0.174	NA	0.143	0.160	237
20-Apr-16	0.035	0.074	0.056	0.074	0.113	316
21-Apr-16	0.200	0.188	0.086	0.084	0.162	321

Note: NA = Not available due to pump malfunction.

Table 3

Gravimetric time-weighted-average respirable dust concentrations for underneath the roof bolter canopies and for roof bolter operators.

Date	Right side under canopy concentration (mg/m^3)	Left side under canopy concentration (mg/m^3)	Right side operator concentration (mg/m^3)	Left side operator concentration (mg/m^3)	Time (min)
19-Apr-16	0.096	0.114	0.221	0.218	237
20-Apr-16	0.022	0.024	0.120	0.112	316
21-Apr-16	0.088	0.093	0.196	0.232	321

Table 4

Gravimetric time-weighted-average respirable dust concentrations for the continuous miner intake and return.

Date	Intake concentration (mg/m^3)	Return concentration (mg/m^3)	Time (Min)
19-Apr-16	0.033	0.417	237
20-Apr-16	0.063	0.384	316
21-Apr-15	0.151	0.330	321

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Table 5

Airflow velocities measured underneath the canopy air curtain.

Date	Right side under canopy airflow velocity (m/s)	Left side under canopy airflow velocity (m/s)
19-Apr-16	NA	NA
20-Apr-16	0.78	1.35
21-Apr-16	0.137	1.32

Note: NA = Not available.

Table 6

Respirable dust control efficiency for right side canopy air curtain on April 19th.

Entry/place	Time (min)	Underneath canopy right personal concentration (mg/m^3)	Time (min)	Outside canopy right personal concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
8	37	0.146	68	0.322	54.7	No	4.96	10
7	7	0.130	111	0.187	30.2	No	2.90	2

Table 7

Respirable dust control efficiency for left side canopy air curtain on April 19th.

Entry/place	Time (min)	Underneath canopy left personal concentration (mg/m^3)	Time (min)	Outside canopy left personal concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
8	35	0.170	72	0.430	60.4	Yes	4.96	10
7	10	0.085	111	0.098	13.4	No	2.90	2

Table 8

Respirable dust control efficiency for right side canopy air curtain on April 20th.

Entry/place	Time (min)	Underneath canopy right personal concentration (mg/m^3)	Time (min)	Outside canopy right personal concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	36	0.124	37	0.065	−91.4	No	4.30	8
8	42	0.154	44	0.109	−41.2	No	3.06	10
9	26	0.036	128	0.084	57.1	No	2.33	7

Table 9

Respirable dust control efficiency for left side canopy air curtain on April 20th.

Entry/place	Time (min)	Underneath canopy left personal concentration (mg/m^3)	Time (min)	Outside canopy left personal concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	33	0.087	39	0.110	21.2	Yes	4.30	8
8	46	0.103	43	0.164	21.2	No	3.06	10
9	22	0.101	32	0.072	36.9	No	2.33	7

Table 10

Respirable dust control efficiency for right side canopy air curtain on April 21st.

Entry/place	Time (min)	Underneath canopy right personal concentration (mg/m^3)	Time (min)	Outside canopy right personal concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	30	0.138	40	0.093	−48.7	Yes	2.88	7
9 right	8	0.086	13	0.084	−2.1	No	8.07	2
9 left	43	0.105	28	0.094	−12.4	No	8.07	10
9	43	0.328	53	0.496	33.8	No	2.94	11
8 left	35	0.086	19	0.089	3.2	No	7.37	11

Table 11

Respirable dust control efficiency for left side canopy air curtain on April 21st.

Entry/place	Time (min)	Underneath canopy left personal concentration (mg/m^3)	Time (min)	Outside canopy left personal concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	28	0.424	44	0.369	−14.9	No	2.88	7
9 Right	8	0.110	13	0.128	14.4	No	8.07	2
9 Left	42	0.175	26	0.114	−53.9	Yes	8.07	10
9	46	0.167	49	0.258	35.3	No	2.94	11
8 Left	37	0.188	18	0.255	26.3	Yes	7.37	11

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Table 12

Respirable dust control efficiency for right side canopy air curtain compared to sampler at the rear of roof bolter machine on April 19th.

Entry/ Place	Time (min)	Underneath canopy right personal concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
8	37	0.146	0.072	−101.3	No	4.96	10
7	7	0.130	0.046	−184.4	No	2.90	2

Table 13

Respirable dust control efficiency for left side canopy air curtain compared to sampler at the rear of roof bolter machine on April 19th.

Entry/place	Time (min)	Underneath canopy left personal concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
8	35	0.170	0.072	−135.2	Yes	4.96	10
7	10	0.085	0.046	−85.6	No	2.90	2

Table 14

Respirable dust control efficiency for right side canopy air curtain compared to sampler at the rear of roof bolter machine on April 20th.

Entry/place	Time (min)	Underneath canopy right personal concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	36	0.124	0.109	−13.8	No	4.30	8
8	42	0.154	0.109	−57.2	No	3.06	10
9	26	0.036	0.080	55.1	No	2.33	7

Table 15

Respirable dust control efficiency for left side canopy air curtain compared to sampler at the rear of roof bolter machine on April 20th.

Entry/place	Time (min)	Underneath canopy left personal concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	33	0.087	0.109	20.5	No	4.30	8
8	46	0.103	0.098	20.5	No	3.06	10
9	22	0.101	0.080	−5.7	No	2.33	7

Table 16

Respirable dust control efficiency for right side canopy air curtain compared to sampler at the rear of roof bolter machine on April 21st.

Entry/place	Time (min)	Underneath canopy right personal concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	30	0.138	0.169	18.6	No	2.88	7
9 Right	8	0.086	0.037	−132.8	No	8.07	2
9 Left	43	0.105	0.125	−15.8	Yes	8.07	10
9	43	0.328	0.614	46.5	No	2.94	11
8 Left	35	0.086	0.179	52.2	Yes	7.37	11

Table 17

Respirable dust control efficiency for left side canopy air curtain compared to sampler at the rear of roof bolter machine on April 21st.

Entry/place	Time (min)	Underneath canopy left personal concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	28	0.424	0.169	−150.5	Yes	2.88	7
9 right	8	0.110	0.037	−197.6	No	8.07	2
9 left	42	0.175	0.125	−40.0	Yes	8.07	10
9	46	0.167	0.614	72.9	No	2.94	11
8 left	37	0.188	0.179	−4.6	Yes	7.37	11

Table 18

Respirable dust control efficiency for right underside canopy air curtain compared to sampler at the rear of roof bolter machine on April 19th.

Entry/place	Time (min)	Right underside concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
8	37	0.064	0.072	12.3	No	4.96	10
7	7	0.057	0.046	−23.9	No	2.90	2

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Table 19

Respirable dust control efficiency for left underside canopy air curtain compared to sampler at the rear of roof bolter machine on April 19th.

Entry/place	Time (min)	Left underside concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
8	35	0.088	0.072	−21.2	No	4.96	10
7	10	0.044	0.046	4.3	No	2.90	2

Table 20

Respirable dust control efficiency for right underside canopy air curtain compared to sampler at the rear of roof bolter machine on April 20th.

Entry/place	Time (min)	Right underside concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	36	0.023	0.109	78.9	Yes	4.30	8
8	42	0.029	0.109	70.8	Yes	3.06	10
9	26	0.007	0.080	91.5	Yes	2.33	7

Table 21

Respirable dust control efficiency for left underside canopy air curtain compared to sampler at the rear of roof bolter machine on April 20th.

Entry/place	Time (min)	Right underside concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	33	0.018	0.109	83.1	Yes	4.30	8
8	46	0.022	0.098	83.1	Yes	3.06	10
9	22	0.021	0.080	77.6	Yes	2.33	7

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Table 22

Respirable dust control efficiency for right underside canopy air curtain compared to sampler at the rear of roof bolter machine on April 21st.

Entry/place	Time (min)	Right underside concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	30	0.062	0.169	63.6	Yes	2.88	7
9 Right	8	0.038	0.037	−4.3	No	8.07	2
9 Left	43	0.047	0.125	62.3	Yes	8.07	10
9	43	0.147	0.614	76.0	Yes	2.94	11
8 Left	35	0.038	0.179	78.6	Yes	7.37	11

Table 23

Respirable dust control efficiency for left underside canopy air curtain compared to sampler at the rear of roof bolter machine on April 21st.

Entry/place	Time (min)	Left underside concentration (mg/m^3)	Roof bolter rear concentration (mg/m^3)	Control efficiency (%)	Statistically significant (95%)	Vent airflow (m^3/s)	Number of rows
7	28	0.169	0.169	−0.2	No	2.88	7
9 Right	8	0.044	0.037	−19.0	No	8.07	2
9 Left	42	0.074	0.125	40.7	Yes	8.07	10
9	46	0.067	0.614	89.1	Yes	2.94	11
8 Left	37	0.075	0.179	58.2	Yes	7.37	11