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Development of a roof bolter canopy air curtain for respirable dust control

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Abstract

Testing of the roof bolter canopy air curtain (CAC) designed by the U.S. National Institute for Occupational Safety and Health (NIOSH) has gone through many iterations, demonstrating successful dust control performance under controlled laboratory conditions. J.H. Fletcher & Co., an original equipment manufacturer of mining equipment, further developed the concept by incorporating it into the design of its roof bolting machines. In the present work, laboratory testing was conducted, showing dust control efficiencies ranging from 17.2 to 24.5 percent. Subsequent computational fluid dynamics (CFD) analysis revealed limitations in the design, and a potential improvement was analyzed and recommended. As a result, a new CAC design is being developed, incorporating the results of the testing and CFD analysis.

Introduction

Exposure to respirable coal mine dust can cause coal workers' pneumoconiosis (CWP), also known as black lung. If silica is present in the dust, the miner may develop silicosis in addition to CWP. CWP and silicosis are occupational respiratory diseases that are ultimately fatal and have no cure. The only method of prevention is to eliminate exposure to respirable coal mine dust and crystalline silica, or quartz. The occupational exposure limit on a Mining Research Establishment (MRE) basis for respirable coal mine dust had been 2 mg/m^3 during each shift that a miner is exposed in the active workings of the mine or in mine facilities. Under recently enacted legislation, this standard was changed in August 2016 to 1.5 mg/m^3 for a full working shift (The Office of the Federal Register, 30 CFR 70.100, 2015). When respirable quartz is present, the mine must maintain its average concentration at or below 0.1 mg/m^3. If the mine exceeds the 0.1 mg/m^3 respirable quartz dust concentration, then the applicable respirable dust standard is reduced, calculated as 10 divided by the percentage of quartz present (The Office of the Federal Register, 30 CFR 70.101, 2015).

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The sources of exposure to respirable coal mine dust for roof bolting occupations include infrequent maintenance and cleaning of the vacuum dust collection system and operating the bolter downwind — in the return air — of the continuous miner (Goodman and Organiscak, 2003). Recent studies have demonstrated that vacuum dust collection systems are effective in capturing bolter-generated dust if maintained and operated correctly and if proper face ventilation techniques are used. However, most exposure to respirable coal mine dust for a roof bolter occurs when the roof bolter machine is operated downwind of the continuous miner (Potts, Reed and Colinet, 2011; Colinet, Reed and Potts, 2013). Because of this higher exposure downwind of the continuous miner, the roof bolter is often limited to working downwind of the miner only once during a production shift.

To prevent overexposure for roof bolter operators, research and development have been underway to design engineering control in the form of the canopy air curtain (CAC). Intended to protect workers from airborne dust exposure, the CAC uses a blower fan with a filtered intake to move clean air to a canopy that is located on the underside of the bolting machine canopy above the miner. The filtered air blows over the miner's breathing zone to reduce exposure to the dust-laden air. Application of a CAC in the mining industry was originally developed under a U.S. Bureau of Mines (USBM) contract by Donaldson Co. for use on continuous miners when cabs were incorporated into the rears of the continuous miner bodies (Krisko, 1975).

Limited successful field-testing of the CAC was completed on continuous miners. The testing showed that the performance of the CAC for dust control was variable. The respirable coal mine dust reductions of the CAC ranged from 23 to 69 percent. Krisko (1975) noted that the portion of total time the operator spent underneath the CAC was highly important in determining the effectiveness of the CAC.

In the United Kingdom, the National Coal Board Mining Research and Development Establishment's Dust Branch, which is a U.K. government entity, field-tested the initial USBM design in both blowing and exhausting face ventilation configurations on an underground cutting machine. Personal dust sampling was conducted with a sampler affixed to the miner's hard hat. The concentrations outside of the canopy were measured using a sampler mounted just outside the canopy. In the blowing ventilation, CAC use during cutting reduced dust concentrations to 9.2 mg/m^3 from 18.6 mg/m^3, equivalent to a 48 percent reduction. In the exhausting ventilation, CAC use during cutting reduced dust concentrations to 2.7 mg/m^3 from 7.3 mg/m^3, equivalent to a 66 percent reduction (European Communities Commission, 1981). As noted by Krisko (1975), the time the operator spent directly under the canopy greatly affected its effectiveness.

The CAC concept can also be applied to the roof bolter to prevent respirable coal mine dust overexposure. The U.S. National Institute for Occupational Safety and Health (NIOSH) designed a new prototype CAC for retrofit installation onto a roof bolter (Listak and Beck, 2012), following other previously investigated designs (European Communities Commission, 1983; Engel et al., 1987; Goodman and Organiscak, 2001, 2003). This larger CAC design provided increased area coverage based upon a typical existing roof bolter canopy size and could be easily retrofitted to an existing roof bolter canopy. The resulting prototype, termed the NIOSH CAC, retained all of the important design considerations of the original CAC design. Laboratory testing showed dust control efficiencies ranging from 67 to 75 percent with the NIOSH CAC (Listak and Beck, 2012).

However, although the laboratory results were promising, implementing the NIOSH CAC in the field proved to be difficult. Limited data showed the CAC has the possibility to be successful with reductions of 35 to 53 percent under the canopy (Listak and Beck, 2012).

Fletcher CAC

J.H. Fletcher & Co. began implementing the CAC on its roof bolters as a dust control device and made notable changes to the NIOSH CAC. The primary change is that the CAC is incorporated into the roof bolter canopy at the design stage instead of being an add-on device. The bolting machine's hydraulic system is used to operate the filtered-air blower fan that provides the clean air to the CAC, and a new horizontal outlet design was built using slotted openings instead of a perforated plate with screen mesh backing. The slotted design resulted in a perimeter airflow pattern, which had not previously been tested. These design changes revised the NIOSH CAC prototype substantially. The advantages of the revised prototype, termed Fletcher CAC, are that it has a much thinner profile and is incorporated into the existing machine design, making it much simpler to operate.

Fletcher provided a redesigned prototype CAC to NIOSH for testing in the laboratory setting (Fig. 1), and it was tested for respirable dust control effectiveness. The Fletcher design consisted of a removable plate with slots cut around the perimeter of the plate. The specifications of the plate openings are listed in Table 1.

Test procedure

Testing of the Fletcher CAC was conducted in two phases. In the first phase, the velocity profile of the air distribution from the plenum was measured. In the second phase, the effectiveness of the Fletcher CAC for respirable dust control was tested. During these two phases, approximately 0.142 m^3/s (300 cfm) of airflow was supplied to the canopy plenum. This airflow was filtered using a Donaldson P123990 filter (Donaldson Co., Bloomington, MN) with an efficiency rating of 99.9 percent. The test procedures followed protocols developed for CAC testing by Listak and Beck (2012) and Goodman and Organiscak (2003).

Air velocity measurement

To determine the air velocity profile of the Fletcher CAC, a test stand was built to support the CAC, and a grid measuring 10.2 by 10.2 cm (4 by 4 in.) was placed 25.4 cm (10 in.) below and in the same plane as the plenum face. The measurement grid extended approximately 30.5 cm (12 in.) beyond the perimeter of the Fletcher CAC. The velocity distribution test was then repeated with the measurement grid 76.2 cm (30 in.) below the Fletcher CAC.

Table 2 lists the airflow velocity information for the Fletcher design, and the air velocity profiles are presented in Fig. 2. Higher CAC air velocities were observed near the front of the Fletcher CAC. The airflow supply is directed toward the front of the Fletcher CAC, by design, and an internal angle plate directs the airflow downward, forcing greater downward airflow at the front. This phenomenon results in the higher velocities being located toward the front of the CAC. Overall, the downward airflow velocity from the Fletcher designed plenum was greater than the airflow from the NIOSH design, with a maximum velocity of 3.82 m/s (751 ft/min) for the Fletcher design compared with 2.29 m/s (450 ft/min) for the NIOSH design.

Respirable dust control effectiveness

Testing for respirable dust control was performed in the NIOSH model long-wall gallery return section. The return section was 2.29 m (90 in.) high and 1.98 m (78 in.) wide. The Fletcher CAC was centered in the return with the slotted distribution plate surface 1.83 m (72 in.) above the floor. The Fletcher CAC was placed approximately 24.4 m (80 ft) downwind of the dust feeder. The dust used for testing was a fine-sized coal dust, with 80 percent passing 20 μm, consisting of Keystone 325BA Mineral Black Filler (Keystone Filler & Manufacturing Co., Muncy, PA).

Both gravimetric and instantaneous samplers were used for testing the Fletcher CAC. The gravimetric samplers consisted of 10-mm (0.4-in.) Dorr-Oliver cyclones and 37-mm (1.5 in.) 5-μm polyvinyl chloride filters with a vacuum pump providing a sampling airflow of 2 L/min (0.07 cfm) regulated by individual critical orifices. The instantaneous samplers were personal DataRAM pDR-1000 nephelometers (Thermo Fisher Scientific, Waltham, MA). A sampling package comprising two gravimetric and one instantaneous sampler was used to sample respirable dust at a location 1.52 m (5 ft) upstream of the CAC test stand in the center of the entry at the same vertical position as the air distribution plate. This sampling package was used to monitor the respirable upstream dust concentration throughout the test. A similar sampling package was also placed downstream 1.52 m (5 ft) from the CAC test stand, also in the center of the entry. To test the Fletcher CAC for dust control effectiveness, six gravimetric samplers were placed 25.4 cm (10 in.) and 76.2 cm (30 in.) below the Fletcher CAC (see Fig. 1 for sampler locations).

Nominal ventilation air velocities of 0.05 m/s (10 ft/min), 0.3 m/s (60 ft/min), and 0.6 m/s (120 ft/min) were established in the return section where the CAC test stand was located. The orientation of the Fletcher CAC to the ventilation airflow is shown in Fig. 1. The velocities in the entry were verified prior to and after testing using a vane anemometer. A dust feeder was used to introduce dust into a pressurized airflow stream through a conduit system with a 2.5-cm (1-in.) diameter outlet in the longwall gallery, aiming to obtain an upwind respirable dust concentration of approximately 6.0 mg/m^3. This target concentration was selected because previous NIOSH studies had shown that this level of dust concentration is encountered in the return of continuous miners using scrubbers (Listak and Beck, 2012; Colinet, Reed and Potts, 2013; Potts, Reed and Colinet, 2011). The pDR-1000 instantaneous samplers were used to monitor dust concentrations during testing.

After the test dust concentration had developed, the evaluation proceeded, testing the Fletcher CAC with the air supply blower off, or canopy off, as the baseline condition and then the air supply blower turned on, or canopy on, as the test condition. Dust concentrations were measured for 30 minutes in each condition.

Because the upwind dust concentration varied between tests, the ratio of the average of the six undercanopy gravimetric samplers to the average of the two upwind gravimetric samplers was used to assess the effect of the Fletcher CAC. The upwind gravimetric samplers were designated 1 and 2, while the undercanopy gravimetric samplers were designated A through F. The ratio for each test condition, with canopy blower on, and each baseline condition, with canopy blower off, was determined by:

$$ratio=\frac{canopy}{upwind}$$

where *canopy* is the average of the six respirable dust concentrations, A through F, below the canopy and *upwind* is the average of the two upwind respirable dust concentrations, 1 and 2.

The dust control efficiency was calculated by comparing the ratios from the canopy on and canopy off trials using the following equation:

$$Efficiency=\left(1-\left(\frac{ratio\ on}{ratio\ off}\right)\right)\times 100$$

where *ratio on* is the ratio from the canopy on trial and *ratio off* is the ratio from the canopy off trial.

The test results are presented in Table 3. Dust control efficiencies were calculated from the ratios, and the data sets were evaluated to determine if the averages from the canopy off and canopy on were statistically different. The t-test using a 95 percent significance level was applied in this evaluation (Natrella, 1963). In all cases, there was a statistically significant difference between the two data sets of canopy off ratio and canopy on ratio.

The testing parameters for the Fletcher CAC test were essentially the same as for the NIOSH CAC tests but with a few variations. The face ventilation airflow for this testing was directed toward the front of the Fletcher CAC instead of the rear as with the NIOSH CAC. The ventilation airflow was measured at the Fletcher CAC instead of at the regulator as for the NIOSH CAC. The dust feed for this testing did not require dispersion. This testing evaluated results from both on and off conditions of the Fletcher CAC and at distances of 25.4 cm (10 in.) and 76.2 cm (30 in.) below the CAC. Finally, the analysis used ratios for evaluation, whereas the NIOSH CAC was evaluated using direct dust concentrations. However, these differences are not perceived to be the cause of the major gap between the NIOSH CAC and the Fletcher CAC results. As seen in Table 3, at the 25.4-cm (10-in.) location below the Fletcher CAC, the reductions of coal mine respirable dust ranged from 17.2 to 24.5 percent, compared with 67 to 75 percent for the NIOSH CAC.

To discover the reason for the lower performance of the Fletcher-designed CAC, NIOSH conducted computational fluid dynamics (CFD) analysis on the Fletcher CAC horizontal outlet slotted openings (Fig. 3) using ANSYS Inc.'s Fluent Version 15.0 CFD software. Single slots were modeled to determine the possible cause of the test results with the Fletcher CAC. Subsequent modeling of double slots was completed to discover if two rows of staggered slots could be a solution to improve reductions of coal mine respirable dust concentrations.

CFD analysis of the Fletcher CAC

An entry that was 1.8 m (6 ft) high, 2 m (6.5 ft) wide and 3 m (10.5 ft) long with the CAC at the roof was modeled to display airflow vectors from the CAC and its influence on dust concentrations in the entry (Fig. 4). Cross-sectional planes are shown to display the effect of airflow vectors on dust concentrations. Input airflow to the CAC slots was set at 300 cfm. Interference or ventilation airflow velocity was 60 ft/min and had a background dust concentration of 6 mg/m^3. Air leakage from the CAC was not considered, that is, all airflow flowed vertically downward from the slots.

Plan views of the dust concentration contour results from the CFD simulation are presented in Fig. 5, showing a limited view of the surrounding area of the CAC domain. The gap between the single row of slots allows the outside airflow to enter the CAC domain — the area inside the slotted perimeter — as can be seen by the higher dust concentrations of 5 to 6 mg/m^3 entering through the gap area (Fig. 5a). The lower downwind dust concentrations are thought to be the result of the influence of higher velocity airflow through the single slot. Double slots would have lower-velocity airflow through them, creating less turbulence immediately downstream. The addition of the second staggered row of slots seems to be effective in preventing outside airflow entering the CAC domain (Fig. 5c). The average respirable dust concentrations directly below the plenum were calculated as 2.72 mg/m^3 for the single-slotted CAC domain (Fig. 5a) and 1.84 mg/m^3 for the double-slotted CAC domain (Fig. 5c). At 25.4 cm (10 in.) below the CAC, the average respirable dust concentrations in the CAC domain were calculated as 4.18 mg/m^3 for the single-row-slotted CAC (Fig. 5b) and 3.43 mg/m^3 for the CAC with the double staggered row of slots (Fig. 5d), indicating that the CAC with the double staggered row of slots provides better protection from coal mine respirable dust than the single-row-slotted CAC.

Reviews of the displays for the YZ cross-sectional planes between slots, or A-A, and on the center of the slot, or B-B, gave similar results, so only the displays for the cross-sectional plane between the slots, A-A, are presented in Fig. 6. The single-row-slotted CAC has a larger area of protection, especially at distances further away from the slot outlets (Fig. 6a). This is due to the higher clean airflow velocity from the CAC, as both the single- and double-slotted CAC are supplied with the same 0.142 m^3/s (300 cfm) airflow amount. But the double-staggered-row CAC has lower dust concentrations within its area of protection (Fig. 6b). The total area of protection from the CAC downward airflow — region with lower dust concentrations — angles downstream due to the influence of the ventilation airflow. This phenomenon occurs for both the YZ plane between the slots, A-A, and the YZ plane in the center of the slot, B-B (not shown). The airflow velocity vectors corroborate the phenomenon, showing how the ventilation airflow affects the downward airflow. For the area of protection directly below the CAC, the single-row-slotted CAC seems to allow the ventilation airflow to enter the CAC domain, especially between the slots (Fig. 6a). The double-staggered-row CAC has an area of recirculation at the rear of the CAC (Fig. 6b). This recirculation area still provides protection to the CAC domain due to the downward airflow from both rows of slots, but it tends to allow ventilation airflow into the CAC domain at the rear of the CAC, albeit at distances further away from the slot outlets.

Reviews of the displays for the XZ cross-sectional planes between the slots, C-C, and on the center of the slot, D-D, gave similar results, so only the displays for the cross-sectional plane C-C are presented in Fig. 7. The single-row-slotted CAC has a better defined area of protection directly below the CAC, especially at distances further away from the slot outlets (Fig. 7a). Again, that is due to the higher airflow velocity at the single slot. The double-staggered-row CAC area of protection tends to expand, especially at distances further away from the CAC slots. Additionally, the double slots have lower dust concentrations within the CAC area of protection (Fig. 7b). This phenomenon occurs for both the XZ plane between the slots, C-C, and the XZ plane on the center of the slot, D-D (not shown). Reviewing the airflow velocity vectors for the single-row-slotted CAC, it seems that some ventilation airflow enters the CAC domain, especially between slots (Fig. 7a). The double-staggered-row CAC provides protection to the CAC domain due to the downward airflow from both rows of slots (Fig. 7b), but it tends to allow ventilation airflow into the CAC domain at distances further away from the slot outlets.

Further examination of the XZ plane airflow velocity vectors shows the airflow from the CAC blowing down to the floor and then returning up along the laboratory walls and returning toward the CAC slot outlets. It is expected that this airflow pattern would translate to what occurs on the rib side of the CAC in an underground entry. However, the opposite side of the CAC would be further away from the rib and the airflow pattern would only be affected by the roof bolter machine itself. Therefore, the airflow pattern on this "off rib" side may be different from that depicted in Fig. 7.

Reviewing the images indicate that adding an additional staggered row or rows of slots behind the original row does help to prevent contaminated ventilation airflow from entering the CAC domain, improving dust control performance. The addition of 80 mesh stainless steel screen on the interior of the horizontal outlet plate may also help to improve dust control performance by ensuring downward airflow through the slots.

Summary and conclusions

Previous laboratory testing had shown that the CAC can be effective as a form of dust control against respirable coal mine dust, but the effectiveness of the CAC for respirable coal mine dust control is still variable. Limited testing in mining applications showed reductions in respirable coal mine dust ranging from 23 to 69 percent.

NIOSH partnered with Fletcher, which has successfully incorporated the CAC on its roof bolters, to improve the performance of the CAC for respirable dust control on underground coal mine roof bolting machines. Laboratory testing of the Fletcher CAC design showed dust reductions ranging from 17 to 24 percent, while previous laboratory testing with the NIOSH CAC design showed dust reductions ranging from 67 to 75 percent.

NIOSH performed CFD analysis of the Fletcher CAC design to determine the cause of the underperformance for respirable coal mine dust control. The analysis showed that the single-slot design allows for contaminated ventilation air to enter the CAC domain, causing the inadequate performance. To improve the CAC design, NIOSH conducted CFD analysis of a design that contained double staggered rows of slots. This design was analyzed to improve the ability of the CAC to provide protection from respirable coal mine dust, with potential improved dust control efficiencies ranging from 43 to 69 percent. The CFD analysis indicated that the key to improvement is preventing ventilation airflow from entering the CAC domain.

As a result of the laboratory test results and CFD analysis, Fletcher is redesigning the CAC for better implementation on the roof bolter for dust control. Improvements include better component placement, including hose routing and guarding; upgraded filtration, by replacing a minimum efficiency reporting value (MERV) 11 filter with a MERV 13 filter; and improved canopy design.

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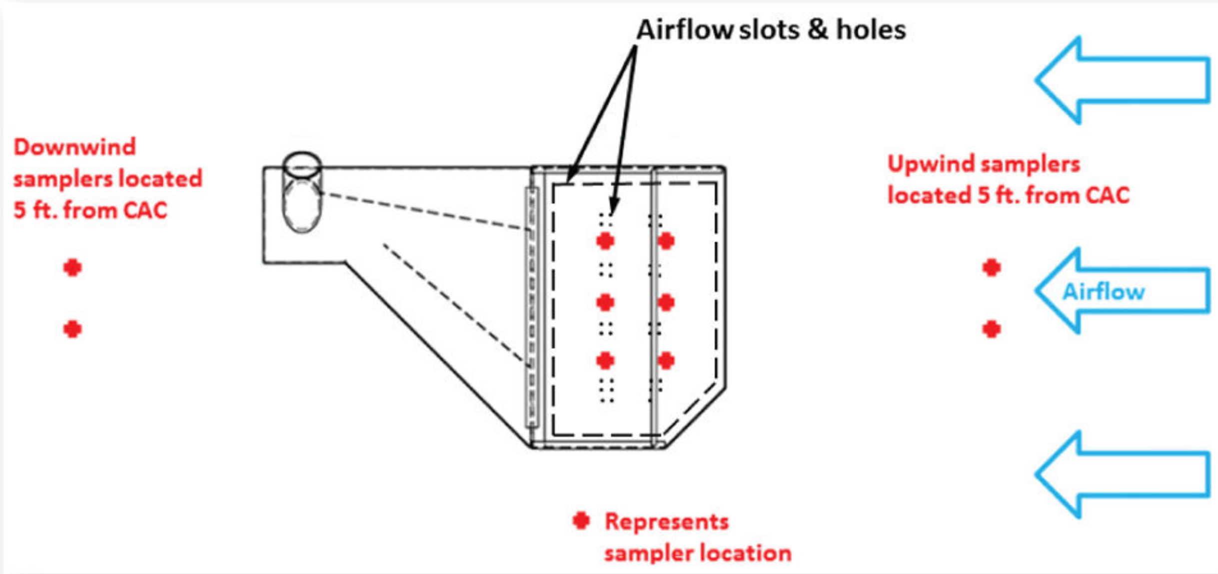

Figure 1.
Underside view of the canopy air curtain (CAC) with Fletcher plate installed, showing airflow slots and holes. Laboratory sampling locations, not to scale, are also shown.

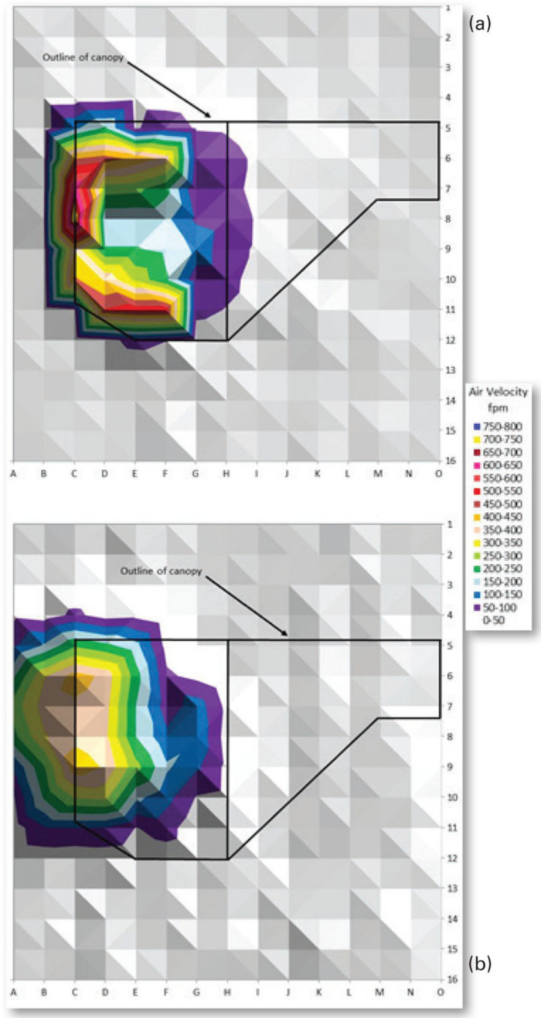

Figure 2.
Airflow velocities at (a) 25.4 cm (10 in.) and (b) 76.2 cm (30 in.) below the Fletcher CAC.

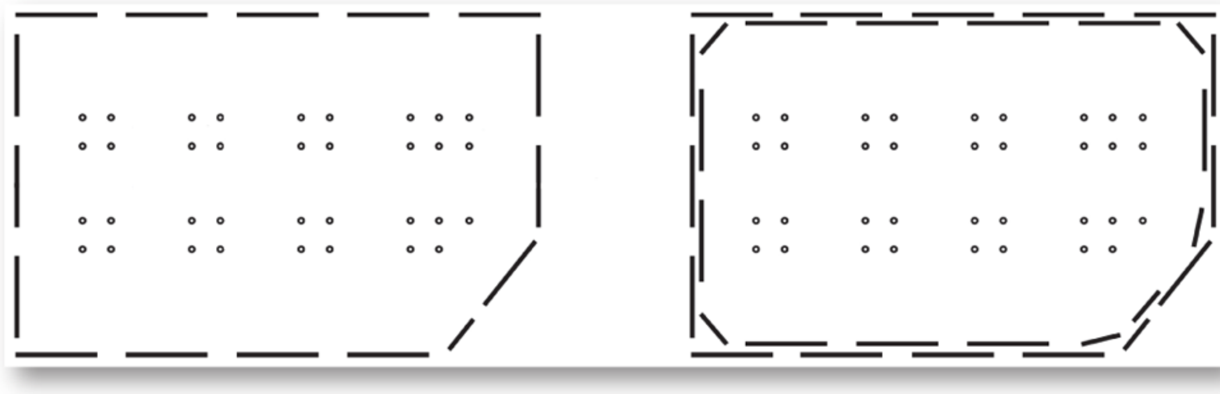

Figure 3.
The canopy air curtain geometric models used in the CFD analysis. The original single-slot design is shown on the left, and the modified double-slot design is on the right.

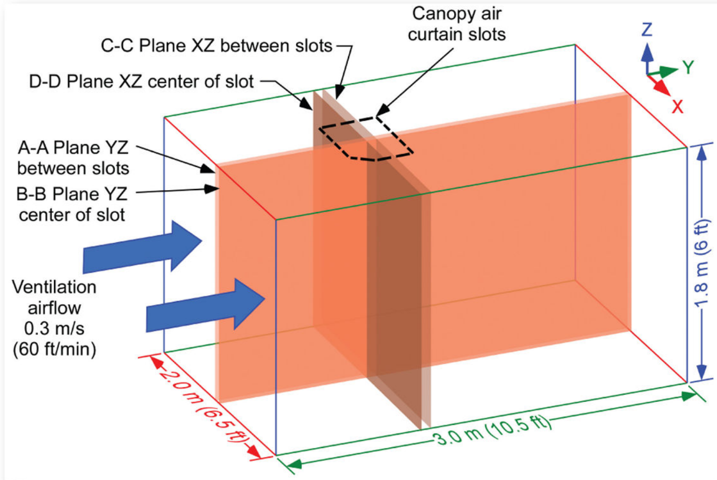

Figure 4.

Geometric volume modeled in CFD software that shows location of CAC slots. Cross-sectional planes are shown to display results of subsequent analysis.

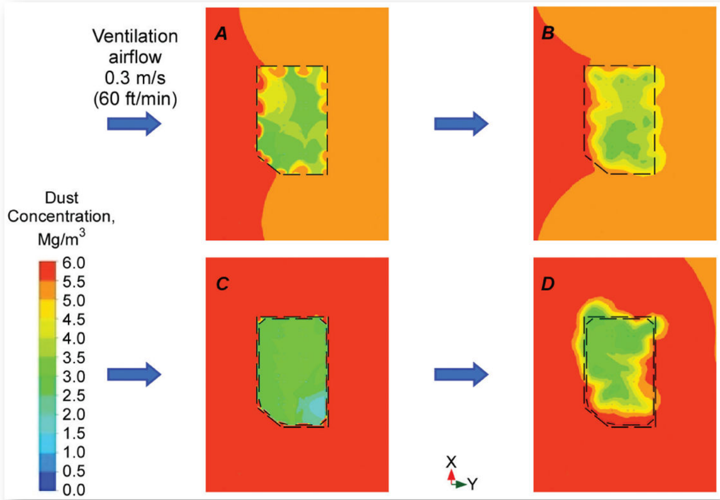

Figure 5.

Plan views of dust concentrations displayed below the canopy air curtain in the XY plane, with only a limited area of the CAC domain displayed: (a) single slots directly below the CAC, (b) single slots 25.4 cm (10 in.) below the CAC, (c) double slots directly below the CAC, and (d) double slots 25.4 cm (10 in.) below the CAC.

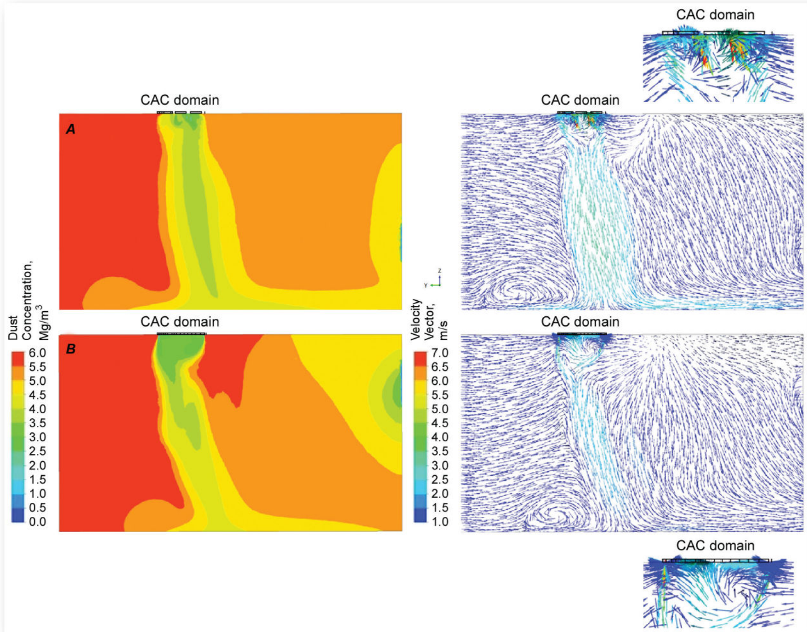

Figure 6.

Cross sections of dust concentrations (left) and airflow vectors (right) in the YZ plane between slots, A-A: (a) single-slot CAC, with right top inset showing zoomed view of canopy area velocity vectors, and (b) double-slotted CAC, with right bottom inset showing zoomed view of canopy area velocity vectors.

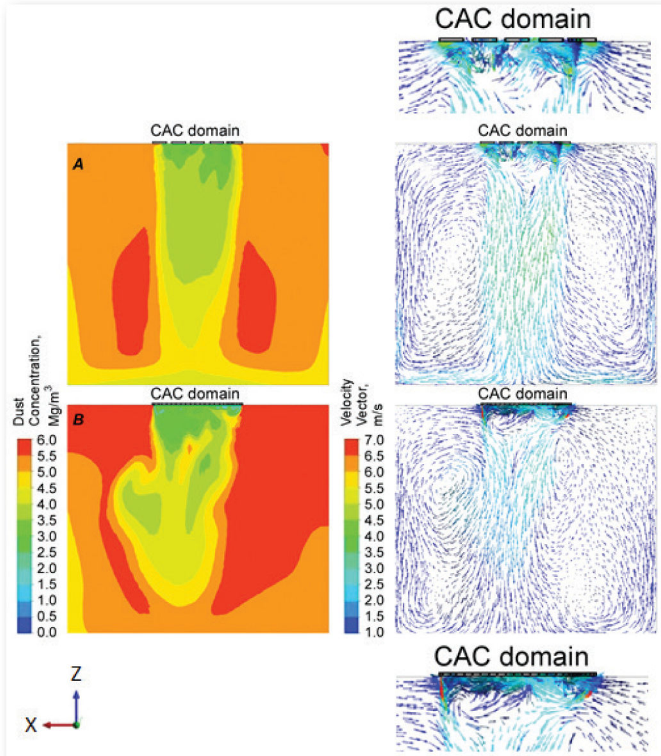

Figure 7.

Cross sections of dust concentrations (left) and airflow vectors (right) in the XZ plane between slots, C-C: (a) single-slot CAC, with right top inset showing zoomed view of canopy area velocity vectors, and (b) double-slotted CAC, with right bottom inset showing zoomed view of canopy area velocity vectors.

Table 1

Specifications of the plate openings used in the Fletcher canopy air curtain.

Fletcher CAC plate design	
Opening type.	Slots and holes.
Opening location.	Slots – perimeter.
	Holes – linear/central.
Opening dimensions.	Slots – 106 × 3 mm (4.1875 × 0.125 in.)
	Holes 6.35 mm diameter (0.25 in.)
Open area.	1.55 percent
Total plate area.	3,406 cm^2 (528 $in.^2$)

Table 2

Airflow statistics for the Fletcher CAC.

Plate	Distance below the canopy (cm)	Maximum airflow velocity (m/s)	Airflow quantity supplied (m^3/s)
Fletcher.	25.4 (10 in.)	3.82 (751 ft/min)	0.142 (300 cfm)
Fletcher.	76.2 (30 in.)	2.18 (429 ft/min)	0.144 (306 cfm)

Table 3

Summary of laboratory dust reductions for Fletcher CAC.

Velocity (m/s)	Distance below the canopy (cm)	Average canopy off ratio (canopy/upwind)	Average canopy on ratio (canopy/upwind)	Dust reduction (%)	Statistically significant? (t-test equal variance, 95%)	Count
0.6 (120 ft/min)	25.4 (10 in.)	1.100	0.911	17.2	Yes.	5
0.3 (60 ft/min)	25.4 (10 in.)	1.048	0.836	20.2	Yes.	5
0.05 (10 ft/min)	25.4 (10 in.)	1.005	0.759	24.5	Yes.	5
0.6 (120 ft/min)	76.2 (30 in.)	1.103	0.941	14.7	Yes.	5
0.3 (60 ft/min)	76.2 (30 in.)	1.088	0.934	14.2	Yes.	5
0.05 (10 ft/min)	76.2 (30 in.)	1.026	0.830	19.2	Yes.	5