

EFFECTS OF AIR-BLOCKING SHELVES ON DUST DISPERSION FOR A DRILL SHROUD USING COMPUTATIONAL FLUID DYNAMICS

Y. Zheng, CDC NIOSH, Pittsburgh, PA
W. R. Reed, CDC NIOSH, Pittsburgh, PA
J. D. Potts, CDC NIOSH, Pittsburgh, PA
M. Li, CDC NIOSH, Pittsburgh, PA
J. P. Rider, NIOSH, Pittsburgh, PA

ABSTRACT

The National Institute for Occupational Safety and Health (NIOSH) has recently developed a series of validated models utilizing computational fluid dynamics (CFD) to study the effects of air-blocking shelves on airflows and respirable dust distribution associated with medium-sized surface blasthole drill shrouds as part of a dry dust collector system. Using validated CFD models, three different air-blocking shelves were included in this study: a 15.2-cm (6-in.) wide shelf; a 7.6-cm (3-in.) wide shelf; and a 7.6-cm (3-in.) wide shelf at four different shelf heights. In addition, the dust-collector-to-bailing airflow ratios of 1.75:1, 1.5:1, 1.25:1, and 1:1 were evaluated for the 15.2-cm (6-in.) wide air-blocking shelf. This paper describes the methodology used to develop the CFD models. The effects of air-blocking shelves and dust-collector-to-bailing airflow ratios were identified by the study, and problem regions were revealed under certain conditions. The simulation results could be used for future development of dust control methods, particularly to address respirable silica dust, for a surface mine blasthole drill shroud.

INTRODUCTION

Surface blasthole drilling can generate considerable amounts of respirable silica dust. These high dust concentrations can be exacerbated by the high silica content as drilling cuts through silica-bearing materials such as sandstone and shale, causing overexposures for miners to respirable silica dust. These overexposures can lead to silicosis, an occupational lung disease that has no cure and is often fatal. A review of the Mine Safety and Health Administration (MSHA) respirable silica dust sample database from 2010 to 2016 for metal/nonmetal mining shows the following overexposure rates for occupations related to blasthole drilling:

- 14.1% of rotary air drillers were overexposed to respirable silica dust (22 out of 156 samples)
- 5.8% of rotary drillers were overexposed to respirable silica dust (9 out of 155 samples)
- 7.3% of drill helpers were overexposed to respirable silica dust (3 out of 41 samples)
- 7.5% of blaster/shotfirer were overexposed to respirable silica dust (3 out of 40 samples)

Of significant interest is an x-ray surveillance study recently completed under the NIOSH Enhanced Coal Workers' Health Surveillance Program (ECWHSP). This program offered free chest radiographs to surface coal miners in 16 states. Pneumoconiosis was found among 2.0% of the 2,328 screened miners with at least 1 year of mining tenure. Twelve miners had radiographic changes consistent with progressive massive fibrosis, and 9 of these 12 miners reported no underground mining tenure. All but 1 of the 9 miners worked at occupations that were in the vicinity of blasthole drilling, either as a driller, blaster, or blast crew member [1].

Many rotary blasthole drilling operations use a dry collection system [2]. Although wet drilling is a better dust control method, it requires a constant water supply, reducing drill bit lives through

excessive bearing wear and hydrogen embrittlement, and causing freezing-related issues in colder climates.

For medium and large drills (such as the Atlas Copco DM45, Sandvik 460, Drilteck D45K, etc.), a typical dry dust collection system schematic is shown in Figure 1. Many studies have been completed on dry dust collectors, so a detailed operational description will not be provided here [3-9]. To summarize the collector operation, compressed air (bailing air) is used to flush the drill cuttings out of the drillhole. The exhaust fan on the collector body is used to pull dusty air and material from the drill shroud into the collector housing, where it is filtered to exhaust clean air.

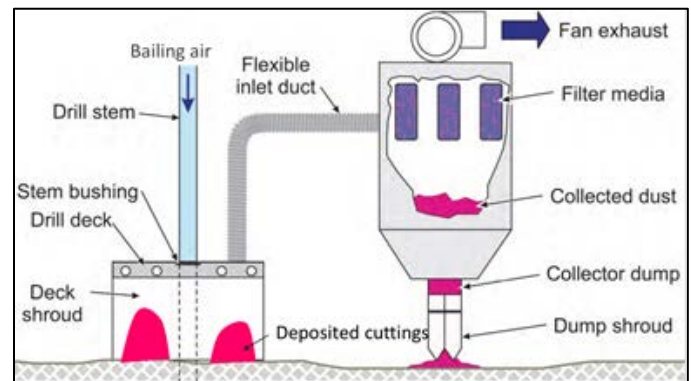


Figure 1. A Basic Dry Dust Collection System on a Drill.

This study focuses on the drill shroud portion of the dust collector. In order to understand the respirable dust behaviors in and around the drill shroud and to develop and evaluate the effectiveness of various control techniques, numerical simulations using computational fluid dynamics (CFD) can be applied to evaluate different scenarios. In order to ensure the correctness of the CFD modeling, previously run experiments conducted in the NIOSH full-scale drill shroud laboratory were utilized to validate the CFD models. Simulation results were compared with the experimental data for a 0.14-m³/s (300-cfm) and a 0.24-m³/s (500-cfm) bailing airflow with 2:1, 3:1, and 4:1 dust collector-to-bailing airflow ratios, having a 5.0-cm (2-in.) gap at the shroud-to-ground interface. The comparison was made evaluating dust concentrations generated from the drill shroud in the lab to those predicted from the simulations. For the CFD simulations conducted using 2:1 and 3:1 ratios, results showed that these models could accurately predict dust generated from laboratory conditions [10].

It was observed in the lab experiments and CFD study that there was a strong Coanda effect inside the drill shroud, in which the bailing airflow from the drill hole flows upward, adhering to the outside surface of the drill steel, then fans out across the underneath side of the drill deck, following down the inside interface/wall of the drill shroud, and then strikes the ground. Due to the openings between the bottom of the shroud and ground caused by uneven or sloping terrain of the

drilling spots, the dusty bailing air has the potential to leak out after it hits the ground.

The experimental data [11-12] and CFD simulation results [10] indicate that the dusty bailing airflow leakage can be greatly reduced when the dust collector-to-bailing airflow ratio increases to 4:1. However, this 4:1 ratio is far more than the common dry dust collector's capacity, which typically provides a 2:1 dust collector-to-bailing airflow ratio [12].

To reduce the dusty air leakage due to the Coanda effect, it is desirable to eliminate or weaken the Coanda effect at least near the shroud-to-ground gap area. An air-blocking shelf was introduced in the mining industry to reduce the dust emissions, and demonstrated about 70% to 81% dust reduction in the field and at the laboratory [8-9].

In this study, CFD simulations are used to reveal the effectiveness of air-blocking shelves. Three different air-blocking shelves were included in this study: a 15.2-cm (6-in.) wide shelf; a 7.6-cm (3-in.) wide shelf; and a 7.6-cm (3-in.) wide shelf at four different heights. The evaluation is based on the CFD-validated models from a previous 0.24-m³/s (500-cfm) bailing airflow with a 2:1 dust collector-to-bailing airflow ratio and a 5.1-cm (2-in.) shroud-to-ground gap. The 15.2-cm (6-in.) wide air-blocking shelf is further evaluated with the dust collector-to-bailing airflow ratios of 1.75:1, 1.5:1, 1.25:1, and 1:1 to assess the value of the ratios with the combination of the air-blocking shelf.

CFD MODELING

The ANSYS Fluent Version 15.0 program was used to perform the analysis of dust distribution in this paper. Using the software drawing tools provided by ANSYS, the schematic of the airflow domain inside the drill table simulator was built according to the geometry measured from the full-sized facility. The facility has been fully described in previous literature [6, 8, 12, 14].

A schematic of the computational domain for three different air-blocking shelves is shown in Figures 2 and 4. The geometric models considered in this study were:

- 15.2-cm (6-in.) wide air-blocking shelf (Figure 2)
- 7.6-cm (3-in.) wide air-blocking shelf (Figure 3)
- 7.6-cm (3-in.) wide air-blocking shelf at four different heights (Figure 4)

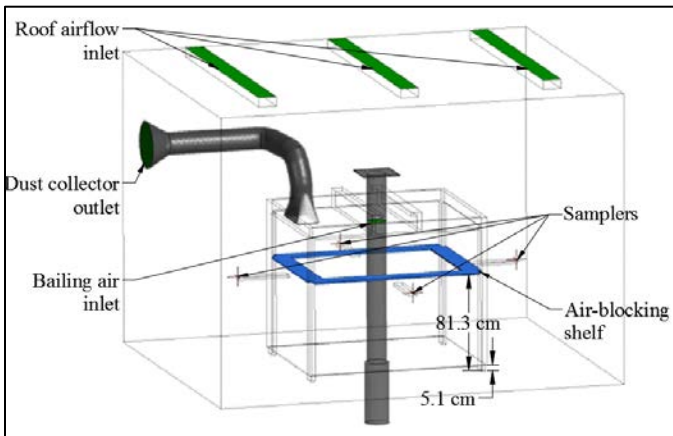


Figure 2. Overview of the CFD Model with Boundary Conditions for a 15.2-cm (6-in.) Wide Air-blocking Shelf.

The boundary conditions applied in the simulation are illustrated in Figure 2. Fresh airflow is pulled into the simulation domain through the three openings on the roof, shown as roof airflow inlets in Figure 2. This airflow compensates for the difference of airflow between the dust collector flow and the bailing airflow, which are set according to the different collector-to-bailing airflow ratios. The dust collector outlet is the only outlet in the simulation domain to allow airflow to exit the laboratory domain. The bailing airflow, together with the roof airflow, enter the domain at the same time. The bailing air with dust is injected

into the simulation domain from a circular face inside the hollow drill pipe, as indicated by the bailing air inlet in Figure 2.

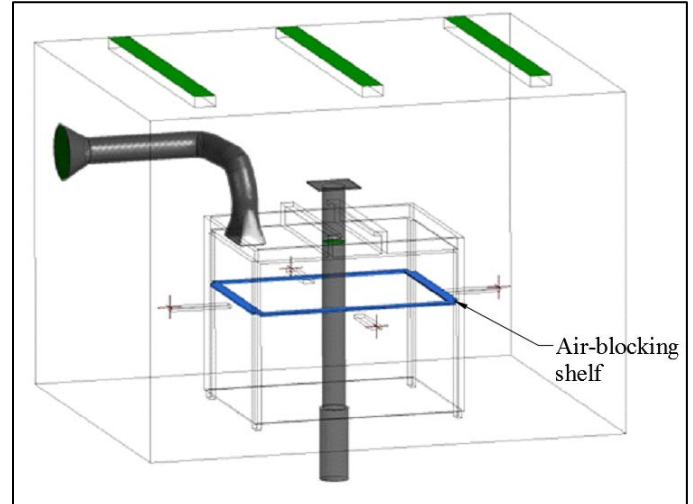


Figure 3. Overview of the CFD Model with Boundary Conditions for a 7.6-cm (3-in.) Wide Air-blocking Shelf.

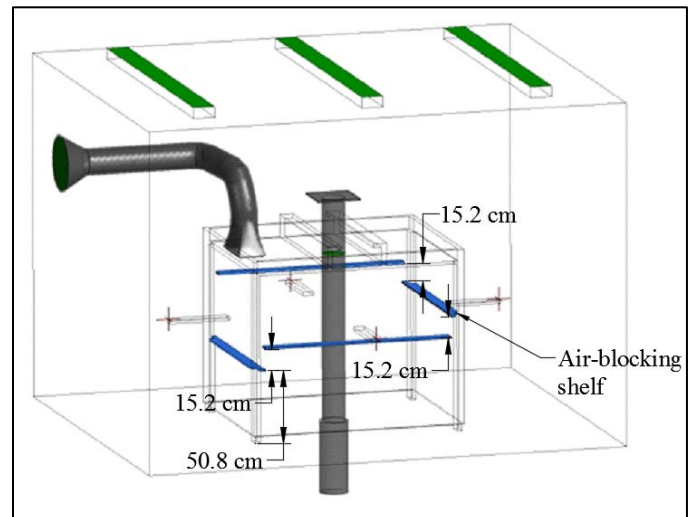


Figure 4. Overview of the CFD Model with Boundary conditions for a 7.6-cm (3-in.) Wide Air-blocking Shelf at Four Levels.

For all the simulation cases, the respirable dust concentrations are collected at the four samplers' locations, as indicated in Figure 2. For both of the simulations with the air-blocking shelf at one level, the shelf is positioned inside the shroud at 2/3 of the total shroud height, which is 81.3 cm (32 in.) above the ground. For the third case with the air-blocking shelf at four different heights, the shelf sides have a 15.2-cm (6-in.) increase in height, starting at the dust collector side and progressing counter-clockwise toward the back of the test facility, with the lowest shelf at 50.8 cm (20 in.) above the ground with no overlap of the shelf vertically, as shown in Figure 4.

Previously validated CFD models were used in this study to evaluate the effect of an air-blocking shelf on dust control. Dust was treated as a gas (CO₂), and a species transport model in Fluent was used. The CFD software uses the steady-state Navier-Stokes equations, continuity equations, and conservation of energy equations as the basic equations to resolve computer models. Turbulence was modeled using the realizable K-epsilon turbulence model with enhanced wall treatment.

In order to ensure simulation accuracy, mesh generation was completed by ensuring high cell density near the drill pipe, at the ground-to-shroud gap, and in the bounding wall regions where high

gradients exist. During mesh generation, the EquiSize Skew was monitored and maintained at a value less than 0.85. Cells that have skewness of 0.90 or more may cause problems with the model results by preventing solution convergence, thus producing inaccurate solutions.

The boundary conditions used to determine the dust distribution inside the NIOSH full-scale drill shroud laboratory are listed in Table 1. The inputs for roof airflow inlet and bailing air inlet are calculated specifically to the test facility dimensions and the desired collector-to-bailing airflow ratios.

Table 1. Input Parameters for CFD Models in Drill Shroud air-blocking Shelf Study.

Simulation setups	Parameter descriptions
Simulation model	Species transport model without reactions
Turbulence model	K-epsilon (k-ε), realizable, enhanced wall condition
Boundary conditions	Roof airflow inlet: velocity inlet (varies according to different collector-to-bailing airflow ratios) Dust collector outlet: pressure outlet (0 Pa) Bailing air inlet: velocity inlet = 11.438 m/s to provide 0.24 m ³ /s (500 cfm) bailing airflow; T = 298.16 K; Dust (CO ₂) mass fraction = 3.07×10^{-5} Others: wall or interior plane
Solution method	Pressure-velocity coupling scheme: SIMPLE Spatial discretization for gradient: Green-Gauss Node-based method; for pressure: PRESTO method; others: 2 nd order upwind scheme.

CHARACTERISTICS OF AIRFLOW AND DUST UNDERNEATH THE DRILL SHROUD

Effect of Different Air-blocking Shelves

The airflow patterns and dust control capabilities were simulated for the three types of air-blocking shelves. They were evaluated under the same ventilation conditions: 0.24 m³/s (500 cfm) of bailing airflow, 0.24 m³/s (500 cfm) of fresh roof airflow, and 0.48 m³/s (1,000 cfm) of dust air mixture collected by the dust collector outlet, which equates to a 2:1 collector-to-bailing airflow ratio.

It can be observed from Figure 5 that, after the dusty air is released from the bailing air inlet, it travels down inside the hollow drill stem, then makes a 180° turn up the gap between the drill steel and drill hole. As the high-velocity air flows up, it follows the outside surface of the drill steel and encounters the underside of the drill deck, where it fans out in all directions and continues to follow the inner shape of the shroud down to where the air-blocking shelf is located.

After the flow encounters the 15.2-cm (6-in.) wide air-blocking shelf, the CFD simulation shows that most of the flow goes horizontally toward the drill steel and then follows the upward bailing air and repeats the pattern while it continues to be drawn in by the dust collector. At the same time, some of the dusty air travels below the air-blocking shelf, where it mixes with fresh airflow that is drawn into the drill shroud through the 5.1-cm (2-in.) shroud to ground gap. The dusty bailing airflow underneath the air-blocking shelf shows a complicated 3D flow pattern due to the combined forces from the dust collector and incoming fresh airflow, but cannot escape under the current conditions outside of the drill shroud.

It can be observed from Figure 5 that the air-blocking shelf hinders the flow of air traveling down the inside wall of the vertical drill shroud and prevents it from directly striking the ground. The airflow above the air-blocking shelf shows a strong Coanda effect, where the airflow tends to attach to nearby surfaces [13], while the airflow below the air-blocking shelf does not show any apparent Coanda effect.

Previous studies [8-10] showed that the Coanda effect causes the dusty bailing air to strike the ground and leak out from the shroud-to-ground gap in the vicinity. The air-blocking shelf effectively eliminates the Coanda effect at the shroud-to-ground gap area. As a result, the respirable dust is confined inside the drill shroud (as clearly indicated in Figure 6), and the miners working nearby should not be exposed to respirable dust from the drill shroud.

The flow pattern for the 7.6-cm (3-in.) wide air-blocking shelf is shown in Figure 7. The main difference in comparison to the 15.2-cm (6-in.) wide air-blocking shelf is that there is not a strong horizontal airflow after the bailing air encounters the 7.6-cm (3-in.) wide air-blocking shelf. In this case, most of the bailing air is diverted toward the lower center of the shroud below the air-blocking shelf. This change in airflow direction diverts the airflow and it strikes the ground away from the vertical walls of the drill shroud, making the dust harder to escape the shroud.

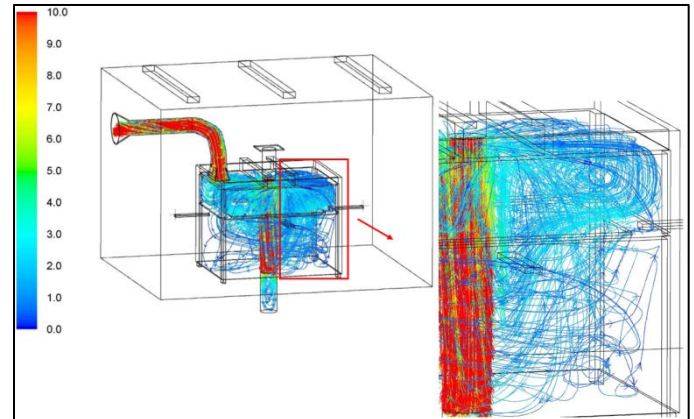


Figure 5. The Pathline of Bailing Airflow Colored by a Velocity Magnitude (0.0–10.0 m/s) with a 15.2-cm (6-in.) Wide Air-blocking Shelf and a Dust-collector-to-bailing Airflow Ratio of 2:1.

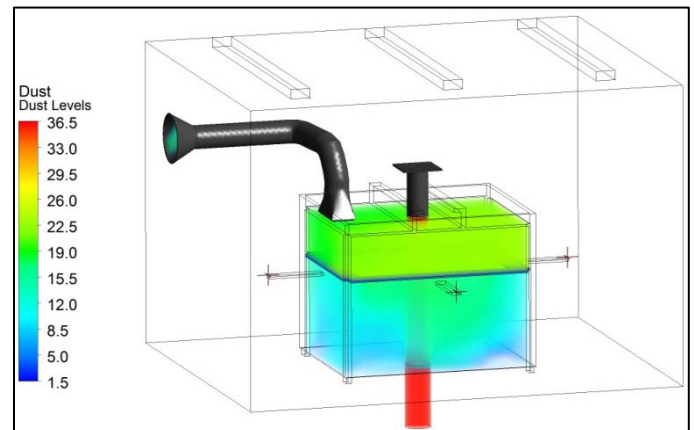


Figure 6. Respirable Dust Concentration Distributions; Legend Shows the Dust Levels (1.5–36.5 mg/m³) with a 15.2-cm (6-in.) Wide Air-blocking Shelf and a Dust-collector-to-bailing Airflow Ratio of 2:1.

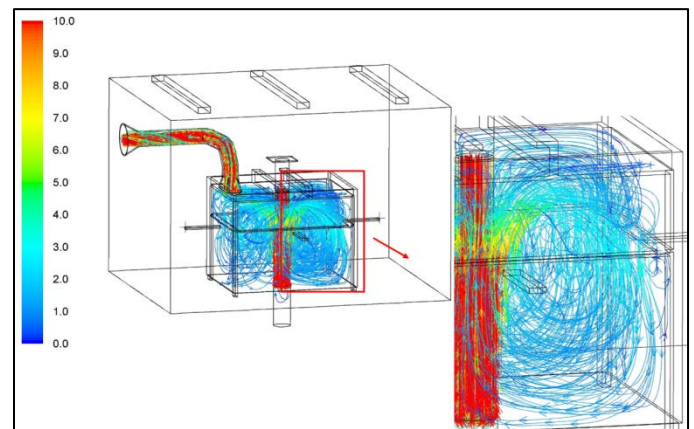


Figure 7. The Pathline of Bailing Airflow Colored by Velocity Magnitude (0.0–10.0 m/s) with a 7.6-cm (3-in.) Wide Air-blocking Shelf and a Dust-collector-to-bailing Airflow Ratio of 2:1.

As shown in Figure 7, airflows traveling down the vertical shroud walls hit the air-blocking shelf, reducing the force of the bailing air that strikes the ground and allowing the respirable dust to be confined inside the shroud as shown in Figures 7 and 8.

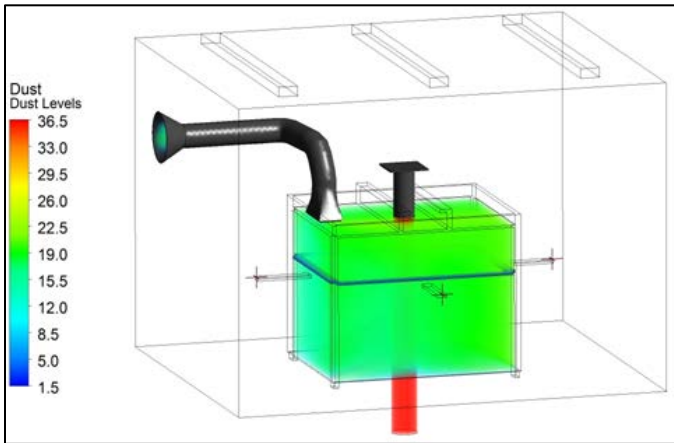


Figure 8. The Respirable Dust Concentration Distributions; Legend Shows the Dust Levels (1.5–36.5 mg/m³) with a 7.6-cm (3-in.) Wide Air-blocking Shelf and a Dust-collector-to-bailing Airflow Ratio of 2:1.

The flow pattern for the 7.6-cm (3-in.) wide air-blocking shelf at four levels is shown in Figure 9. As mentioned earlier, the four shelves attached to the vertical walls had a 15.2-cm (6-in.) increase in height without overlapping vertically. This arrangement can allow the flexibility of the shelf construction to avoid some structure restrictions. The height differences and air-blocking shelf pattern were randomly selected as an example.

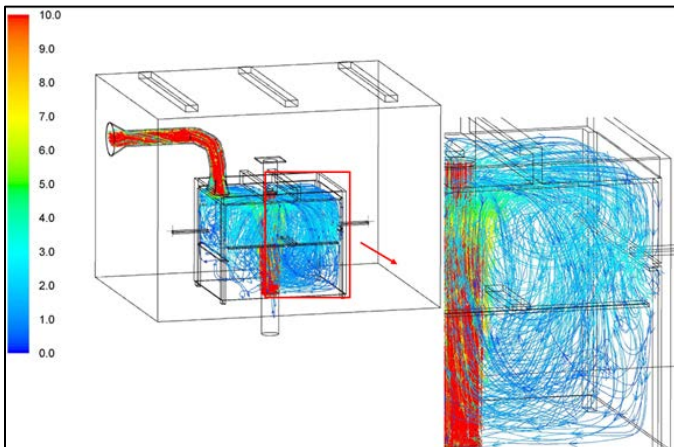


Figure 9. The Pathline of Bailing Airflow Colored by Velocity Magnitude (0.0–10.0 m/s) with a 7.6-cm (3-in.) Wide Air-blocking Shelf at Four Levels and a Dust-collector-to-bailing Airflow Ratio of 2:1.

The results from the CFD simulation in Figure 9 show that pathlines of bailing airflow have similar flow patterns as the 7.6-cm (3-in.) wide air-blocking shelf. Due to the width of this air-blocking shelf, it cannot produce strong horizontal flow after the bailing air hits the shelf as was observed with the 15.2-cm (6-in.) wide air-blocking shelf. However, it still can divert the bailing airflow direction toward the center region of the shroud and reduce the striking ground force, even when there is still some airflow adhering to the shroud's vertical walls below the air-blocking shelf.

This arrangement of air-blocking shelves at different levels can still effectively confine the respirable dust under the 2:1 collector-to-bailing airflow ratio and the 5.1-cm (2-in.) shroud-to-ground gap condition. As shown in Figures 9 and 10, dust does not leak out of the shroud to pollute the surroundings.

Simulation with Different Dust-collector-to-bailing Airflow Ratios

At a 2:1 dust-collector-to-bailing airflow ratio, the CFD simulation revealed that the three types of air-blocking shelves were able to effectively confine the respirable dust inside the drill shroud. However, in a previous study it was shown that the dust-collector-to-bailing airflow ratio was also a critical parameter [10]. In this section, the effect of an air-blocking shelf under different dust-collector-to-bailing airflow ratios is evaluated to investigate whether the ratio is still an important factor.

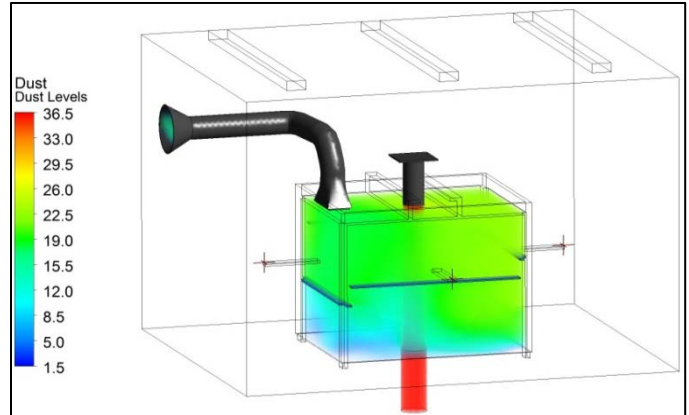


Figure 10. The Respirable Dust Concentration Distributions; Legend Shows the Dust Levels (1.5–36.5 mg/m³) with a 7.6-cm (3-in.) Wide Air-blocking Shelf at Four Levels and a Dust-collector-to-bailing Airflow Ratio of 2:1.

Utilizing the 15.2-cm (6-in.) wide air-blocking shelf, dust control efficiencies were evaluated under different dust-collector-to-bailing airflow ratios. The bailing airflows were kept the same as shown in Table 1, while the fresh roof airflow was calculated to be 0.18 m³/s (375 cfm), 0.12 m³/s (250 cfm), 0.06 m³/s (125 cfm), and 0 m³/s (0 cfm) to represent the collector-to-bailing airflow ratio of 1.75:1, 1.5:1, 1.25:1, and 1:1, respectively.

It can be observed in Figure 11 (a) that the CFD simulation for the 1.75:1 ratio showed the bailing airflow pattern was very similar to the 2:1 ratio case shown in Figure 5. Most of the bailing airflow is diverted horizontally toward the drill steel after it strikes the air-blocking shelf, while some of the dusty bailing air goes below the air-blocking shelf but rarely touches the ground. Several pathlines travel close to the 5.1-cm (2-in.) shroud-to-ground gap, but are drawn back to the dust collector by the incoming fresh airflow. The dust distribution as shown in Figure 12 (a) is totally confined inside the drill shroud for the 1.75:1 ratio case.

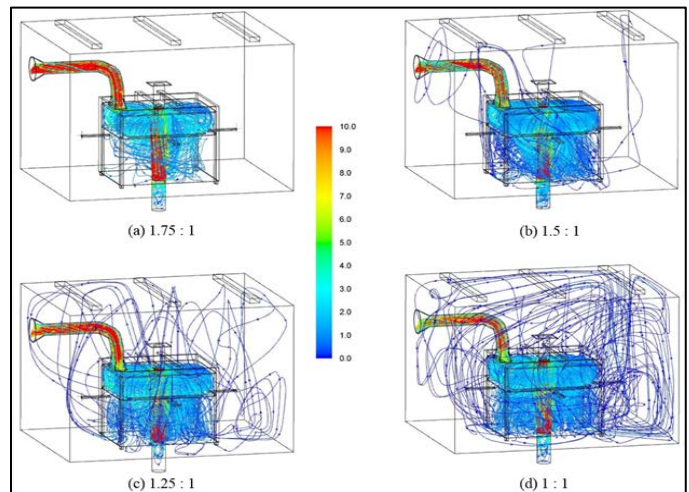


Figure 11. The Pathline of Bailing Airflow Colored by Velocity Magnitude (0.0–10.0 m/s) with 15.2-cm (6-in.) Wide Air-blocking Shelves for Different Dust-collector-to-bailing Airflow Ratios: (a) 1.75:1; (b) 1.5:1; (c) 1.25:1; (d) 1:1.

When the dust-collector-to-bailing airflow ratio is reduced to 1.5:1, as shown in Figure 11 (b), it can be seen that some pathlines start to escape out of the drill shroud at the regions far away from the opening of the dust collector. Due to the decrease in the dust-collector-to-bailing airflow ratio, more dusty bailing air is circulating below the air-blocking shelf and has more of a chance to leak out. The lack of inward airflow at the shroud-to-ground gap, which forces the dusty air away from the shroud-to-ground gap opening, causes leakage at those areas. As a result, as shown in Figure 12 (b), respirable dust escapes outside of the shroud and pollutes the surrounding work region.

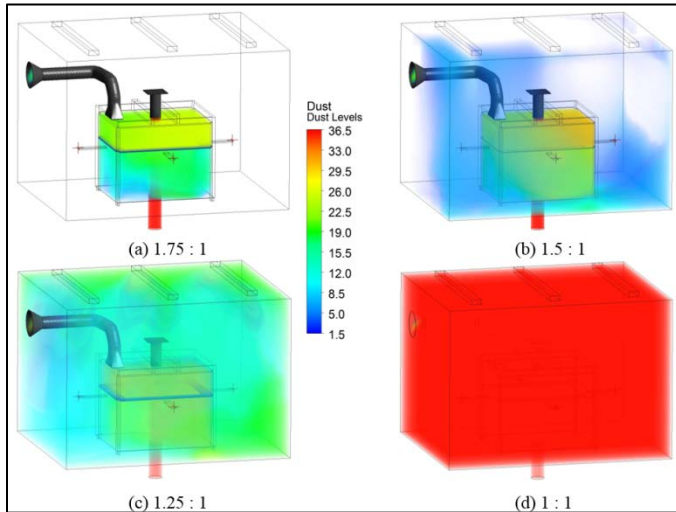


Figure 12. The Respirable Dust Concentration Distributions; Legend Shows the Dust Levels (1.5–36.5 mg/m³) with a 15.2-cm (6-in.) Wide Air-blocking Shelf for Various Dust-collector-to-bailing Airflow Ratios: (a) 1.75:1; (b) 1.5:1; (c) 1.25:1; (d) 1:1.

As the collector-to-bailing airflow decreases, more dusty bailing airflow leaks out as less airflow is drawn in, as shown in Figure 11 (c) for the 1.25:1 collector-to-bailing airflow ratio. At a 1:1 collector-to-bailing airflow ratio, no air flows into the shroud, as shown in Figure 11 (d). The flow patterns for Figure 11 (c) and (d) indicate that the leakage starts at the furthest region away from the dust collector side, but interestingly, these leakage airflows are drawn back inside the drill shroud on the dust collector inlet side. As shown in Figures 12 (b), (c), and (d), respirable dust has leaked outside the drill shroud.

CONCLUSIONS

This study evaluated the dust control capability of three types of air-blocking shelves with different widths and installations. It was found that all three air-blocking shelves can effectively confine the respirable dust inside the drill shroud with no dust leakage under the conditions of a 2:1 dust-collector-to-bailing airflow ratio and a 5.1-cm (2-in.) shroud-to-ground gap. The study was based on a previously validated CFD model.

From the study, it can be observed that the air-blocking shelf can effectively eliminate or greatly reduce the Coanda effect below the shelf and reduce the strike force of the dusty bailing airflow near the shroud-to-ground gap. At the same time, dust-collector-to-bailing airflow ratios are still critical factors in drill shroud dust control. Even with an air-blocking shelf, a low dust collector-to-bailing airflow ratio can still cause serious dust leakage, such as dusty bailing airflow that can freely escape the shroud-to-ground gap without striking the ground. From this study, it is estimated that a dust-collector-to-bailing airflow ratio of at least 1.75:1 needs to be maintained with an air-blocking shelf to effectively confine dust. Without an air-blocking shelf, the same control effect can only be achieved above a 4:1 dust-collector-to-bailing airflow ratio, as revealed previously.

This study can provide guidelines for mining engineer to fully understand the dust problem for the drilling jumbo and drill shroud. It is highly recommended by the study to install the air-blocking shelf and

maintain the dust-collector-to-bailing airflow ratio to protect the miners in the vicinity affecting areas.

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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.

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