CFD modeling of a flooded-bed scrubber concept for a longwall shearer operating in a U.S. coal seam

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The dust generated from mining activities remains a health and safety problem, particularly in underground coal mines. Coal Worker's pneumoconiosis (CWP), colloquially known as 'black lung', is a chronic respiratory disease resulting from extended exposure to respirable coal dust. Corrective actions to mitigate CWP, resulting from the Federal Coal Mine Health and Safety Act of 1969, have significantly reduced the incident rates over the last four decades. However, continuing efforts are needed to control this hazard and the newly mandated dust rule will increase the difficulty for mine operators to maintain compliance. A recent study by the National Institute for Occupational Safety and Health highlighted the ongoing health hazards that remain within the coal mining industry because respirable dust. This is especially true for mines using the longwall mining system due to its high production rates. Further, there are no commercially available dust scrubbers for longwall shearers as there are for continuous miner units. The problem of dust capture in underground coal mines utilizing the longwall mining system is being addressed in this paper.

A conceptual design for a flooded-bed scrubber built into a Joy 7LS longwall shearer is presented. Results from a computational fluid dynamics (CFD) study of the performance of a flooded-bed scrubber design are presented. The CFD study was aimed at maximizing the capture efficiency of the scrubber design while operating in a 2.1 meter (7 ft) coal seam under a variety of scrubber flow rates and mine ventilation conditions.

Keywords: longwall shearer, dust control, flooded bed scrubber, computational fluid dynamics

1. Introduction

Dust generated from mining activity is an inherent problem in mines, particularly for underground mines. Incidences of coal workers' pneumoconiosis, a debilitating respiratory ailment, have declined since the Federal Coal Mine Health and Safety Act of 1969, in the United States. Health hazards due to exposure to elevated dust concentrations of respirable dust still exist, according to the National Institute for Occupational Safety and Health (NIOSH) [1]. The problem with coal dust is not limited to health hazards.

The accumulation of coal dust can create a potentially catastrophic safety hazard. If the dust is not removed, it becomes airborne and will be advected downstream through the mine workings. This readily combustible coal dust must be diluted with rock dust to ensure that it remains inert in the event of a methane ignition. The blast wave from such an ignition can disturb this dust causing it to participate in and greatly enhance the resulting explosion. Such an event occurred at the Upper Big Branch Mine, according to the forensics report prepared by the Mine Safety and Health Administration (MSHA) [2]. Numerous other incidents are documented in the literature.

In the United States, approximately half of the coal produced by underground mines utilize the longwall mining system. According to NIOSH, Longwall operators have historically had a difficult time meeting federal dust standards [3]. The difficulties meeting the dust standard will be aggravated by MSHA's new dust rule, which reduces the dust standard by one fourth. The primary means to deal with dust levels at the longwall face is through dilution with ventilation air, which have increased by about 65% since the mid-1990s [3]. There is a clear need for innovative ways to lower the dust

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level on longwall faces. This work is an effort to adapt flooded-bed scrubbers for use on a longwall shearer.

1.1 Previous efforts for longwall dust control

The Unites States Bureau of Mines began investigating the use of scrubbers for longwall dust control in the 1970s, though the efforts were abandoned by the 1980s [4]. This early research effort was performed under different conditions than is typical of today's longwall mine operations. At the time, unidirectional cutting was common practice, and the quantity of air delivered across the face was much lower.

The research from this former period can be divided into three approaches: ventilated-drum [5] [6], ventilated-cowl (US Patent 4351567), water-powered scrubbers [7], and fan-powered flooded-bed scrubbers [8]. The first three methods relied on high pressure water sprays to move dust laden air into the scrubber inlets, while the last method used a vane-axial fan. High pressure water sprays are compact, allowing them to be mounted within the shearer drum and on the cowl. The main disadvantage of the sprays was the limited airflow capacity compared to fan-powered scrubbers. Their use was also confounded by excessive maintenance issues. For these reasons, water-powered scrubber research was abandoned at that time.

Designs that combined fan-powered flooded-bed scrubbers and longwall shearers were also attempted. Despite its dust reduction potential, the complexity of incorporating the ductwork into the shearer, size constraints, and lack of interest by the industry stalled research in this area. The idea was revisited recently in Australia. Researchers working on a project funded by the Australian Coal Association Research Program developed a fan-powered dust scrubber for a longwall shearer working in a 5 m (16.4 ft) thick coal seam [9]. It was successfully tested at BHP Billiton's Broadmeadow Colliery in the Bowen Basin of North Queensland. Test results demonstrated an overall dust reduction potential of 14% to 56%, depending upon operating conditions and sampling methodology. The scrubber was mounted directly on the leading side of the ranging arm so that it was as close to the drum as possible. Because of its placement, one of the main challenges was developing a prototype that would stand the rigors of mining without being destroyed.

1.2 Flooded-bed scrubber use

In the U.S., the majority of room and pillar coal mines utilize fan-powered flooded-bed scrubbers in their dust control plans. They are considered effective in controlling dust generated at the face. The general arrangement of a fan-powered flooded-bed scrubber (U.S. Patent 4380353) can be seen in Figure 1.

While operating, dust-laden air is drawn in through inlets near the cutting head and into ductwork within the miner. The air and dust passes through a layered-screen bed, typically consisting of 10 to 30 layers of woven steel mesh screens, with an 89 µm (0.0035 in.) wire diameter. An arrangement of one or more full cone nozzles keeps the layered-screen bed wetted with water. As the air and dust pass through the wetted screen, there is a high probability that the dust particles will become encased with water. Increasing the number of layers in the screen tends to increase the likelihood of dust becoming captured by the water, at the expense of increasing pressure drop across the layered-screen bed. The screens are typically installed at an angle to the flow, thereby increasing the available surface area of the bed.

After exiting the layered-screen bed, the air/dust/water mixture flows into the demister. This is an arrangement of parallel, sinuous layers of PVC material, which causes the airflow to make several changes in direction. Due to the mass and speed of the water droplets, their momentum causes them to collide with the layer of plastic. The water and dust then flow down the walls to a collection sump below and is

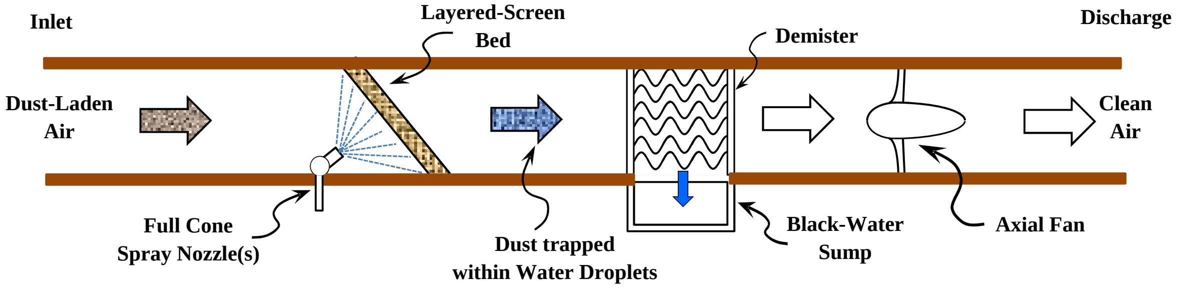

Fig. 1 General arrangement of fan-powered flooded-bed scrubbers

pumped to the miner's discharge conveyor. Clean air exits through the fan, to the scrubber discharge.

The scrubber fan typically ranges in power from 9.7 kW to 30 kW (13 hp to 40 hp), with an airflow range of 1.7 m^3/s to 4.7 m^3/s (3.5 kcfm to 10 kcfm). In the U.S., the airflow through a scrubber is typically slightly lower than the quantity of ventilation air flowing to the face to minimize recirculation. The quantity of air flowing to the face must be no lower than 1.4 m^3/s (3 kcfm) in the U.S., to comply with Federal Law (30 CFR 75.325) and in practice it is usually higher to dilute methane and dust [10].

When considering scrubber systems, two operational characteristics describe the performance of the system as whole, *capture efficiency* and *cleaning efficiency* [4]. *Capture efficiency* is the measure of a system's ability to draw dust laden air into the scrubber; the percentage of dust in the air captured. *Cleaning efficiency* is the measure of a system's ability to remove dust from the air, once it has been captured. According to a study by NIOSH, a fan-powered flooded-bed scrubber, using a 30 layered-screen bed, can achieve a cleaning efficiency greater than 90% [11]. The challenge is capturing the dust laden air before it is diluted by ventilation air.

Longwall ventilation practices are not as conducive to the use of fan-powered flooded-bed scrubbers when compared to room and pillar operations. In a survey conducted by NIOSH in 2007, the average air velocity along a longwall face in the U.S. was found to be 3.38 m/s (665 fpm), with an airflow quantity of 31.6 m^3/s (67 kcfm) [3]. The magnitude of the airflow precludes one from designing a system that matches the airflow quantity through the scrubber to the face quantity, as common with continuous miners. Since only a portion of the air will be captured by the scrubber, the placement of the inlet to the scrubber is critical in achieving a worthwhile capture efficiency. Thus, the inlet must be positioned close to the cutter drum, the principle source of dust on a longwall face [3]. This will allow the scrubber to capture the dust before it is diluted by the ventilation air. Care must be taken in the design to prevent larger coal particles from being ingested by the scrubber in order to prevent excessive clogging. The inlet and ducting must also be protected from spalling coal and rock. It must also not interfere with moving components, such as the ranging arm, cutter drum, or shields.

2. Current research approach

The research approach at the University of Kentucky is a site-specific application of a fan-powered flooded-bed scrubber to a typical U.S. longwall operation in a medium thickness coal seam. The average seam thickness at the mine is 2.1 m (7 ft) and is fairly consistent and flat which is typical of the Pittsburgh coal seam. The longwall face employs a Joy 7LS shearer as seen in Figure 2, courtesy of computer-aided design data (CAD) provided by Joy Global. Although the mine utilizes a bidirectional cutting approach, this research project only addresses the headgate side of the shearer in this initial effort.

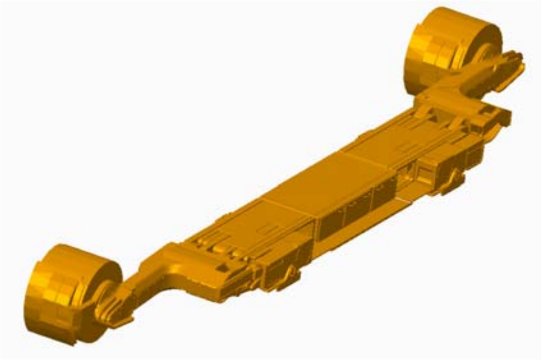

Fig. 2 Joy 7LS longwall shearer employed at the mine specific to the study

2.1 Details from the mine

A visit with the mine personnel yielded additional information to be included in the concept development. The mine operates three development sections utilizing continuous miners and one active longwall panel. The width of the longwall panel is 305 m (1,000 ft). The average longwall retreat rate per day is 34 m (112 ft).

Airflow quantity across the longwall face was controlled by a prescribed mean entry air velocity, according to their ventilation plan. An airflow velocity of no less than 2.5 m/s (500 fpm) at the head gate and a minimum of 2.0 m/s (400 fpm) within 30 m (100 ft) of the tail gate was maintained. This equals a minimum airflow quantity of 14 m^3/s (30 kcfm) maintained in the last open break on the headgate. The ventilation plan included a provision requiring respiratory protection for any persons working more than 12 shields inby the

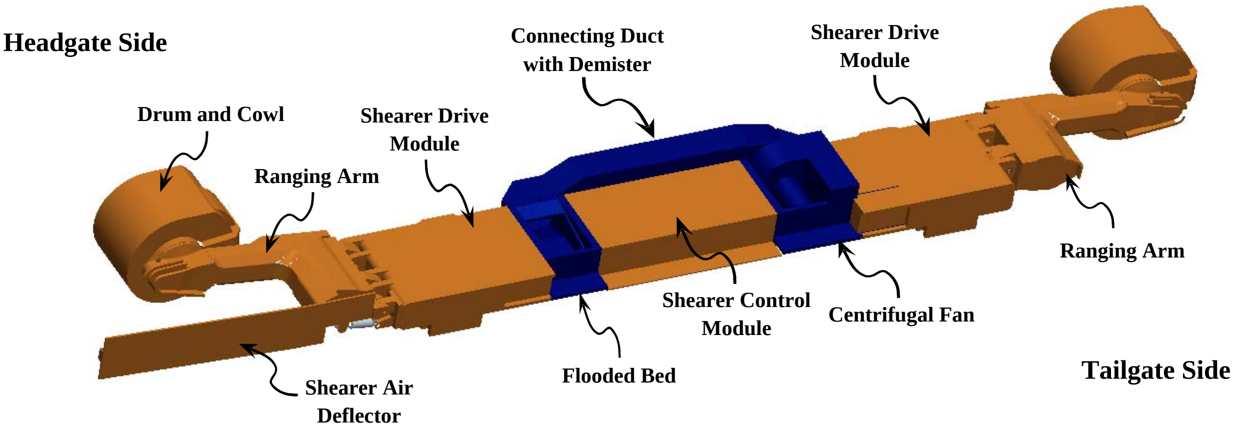

Fig. 3 Conceptual design for incorporating a fan-powered flooded-bed scrubber into a longwall shearer, with inlet and discharge ductwork removed for clarity

shearer while cutting coal due to the expected, elevated concentrations of dust. A shearer air deflector was required to be installed and maintained on the headgate spray arm, which can be seen in Figure 3. This device extends past the head drum and serves to split the air flowing along the face, in an attempt to keep the dust-laden air clear of the walkway where miners are present.

Observations of the shearer in operation highlighted several other concerns. The cutting actions of the headgate drum breaks the coal and sends it forward onto the armored face conveyor, or AFC. This spalled coal flowed out from the drum as it churns which brings a significant cloud of dust forward against the flow of air. A cloud of dust and mist close to the coal on the AFC was pulled along with the moving coal, as it heads to the stageloader. It does not advance far before being overcome by the ventilation air on the face and causing this dust to flow back over the shearer. The velocity of this spalled coal was assumed to depend upon the tangential velocity of the drum, which rotates at approximately 45 rpm. The average speed of the armored face conveyor was found to vary between 1.8 m/s and 2.0 m/s (355 fpm and 400 fpm). These were important observations to include in the CFD model as boundary conditions. This influence of the spalled coal has been included in the CAD model as shown in Figure 4, where the ranging arm can be seen cutting coal.

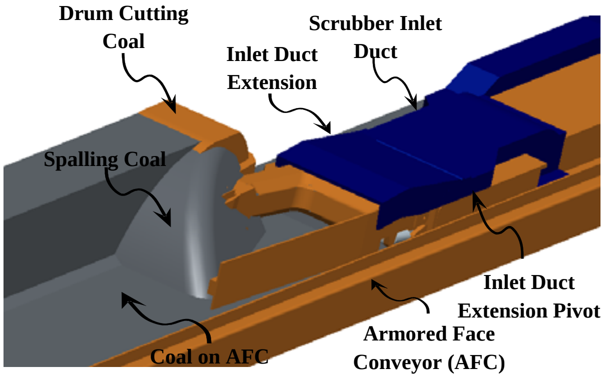

Fig. 4 Conceptual design of inlet duct arrangement and influence of spalling coal due to the actions of the headgate drum

2.2 Conceptual design

Discussions with the engineering team at Joy Global identified key constraints for developing the conceptual design. There is no more than 25 cm (10 in.) of space available above the body of the shearer before it is at risk of hitting a mobile roof support. This was the main constraint when examining where to place scrubber components. As shown in figure 1, there are three main components to a fan-powered flooded-bed scrubber, the flooded-bed, the demister, and the fan, before considering the ductwork. None of these components will fit within a 25 cm height envelope, if the quantity of air delivered to the scrubber is equal to or greater than the quantity of air employed by a continuous mine scrubber. This led to the addition of two new modules to the shearer body, as seen in Figure 3.

To make room for the scrubber components, two new modules were added to the shearer body between the control module and the drive modules. On the headgate side, a compartment for the flooded-bed screen and sprays was added. The screen was angled to maximize the available cross sectional area and its placement is readily accessible for maintenance. The fan was positioned between the control module and the tailgate drive section. Due to the arrangement of the flow, a centrifugal fan was chosen which can readily generate the necessary flow and pressure to power the scrubber. These can be observed in Figure 3. The flooded-bed module added 0.9 m (3 ft) to the length of the shearer, while the fan module added 1.2 m (4 ft). This increased the length of the shearer by 12.5%, from 16.8 m to 18.9 m (55 ft to 62 ft).

A section of ducting connecting the flooded-bed and centrifugal fan was added along the face side of the shearer body, as seen in Figure 3. This was positioned in the void left from the extraction of coal by the leading drum. It projected 0.4 m (1.25 ft) past the edge of the shearer towards the face. Within the duct, the demister and 95 liter (25 gal) black water sump were placed. As the duct is in close proximity to the face, it would be made from thick steel sections limiting the available area for airflow which was taken into account in the CFD model. Conversations with the mine staff indicated that the face side of the control module does not require frequent access for service, meaning the duct would not hamper such activities.

The inlet duct arrangement was critical to the success of the effort. As mentioned in Section 1.2, it is desirable to bring the inlet as close as possible to the dust source, in this case the headgate drum. Several iterations were testing before arriving at the configuration shown in Figure 4. The inlet duct extended up from the flooded-bed module and over the headgate drive module. This occupied the 25 cm (10 in) available height according to engineers at Joy. Like the connecting duct, this would be made of thick steel sections to ensure it survives the rigors of mining. This duct ended at the edge of the headgate drive module, which was insufficient for collecting the dust from the headgate drum. An adjustable extension was added to position the inlet just past the main portion of the ranging arm. It was designed to raise and lower separately so that it may be lowered to clear shields that might be in the way.

3. CFD modeling

CFD modeling is a numerical way of solving fluid dynamics problems. The equations used in this CFD model were the laws of conservation of mass and conservation of momentum. The software used for the simulations was Cradle SC / Tetra version 11, which includes its own preprocessor, solver, and post processor. SC / Tetra utilizes an unstructured mesh approach.

The geometry used for the CFD model was developed in CREO, a three-dimensional parametric modeling package, based upon the data provided by the mine and Joy Global. It includes the longwall shearer, armored face conveyor, the coal face, and a portion of the powered supports. The entire geometry of the powered roof supports was not used, in order to reduce the number of elements, resulting in the simplified geometry used for the domain, as shown in Figure 5.

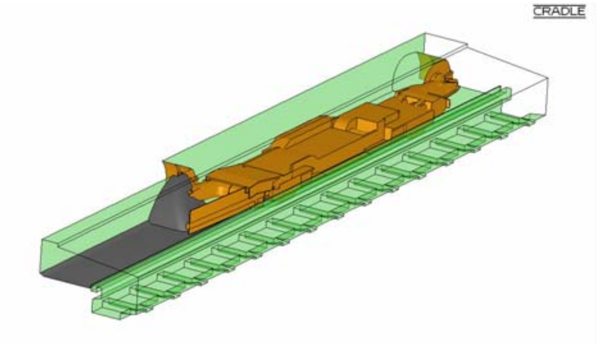

Fig. 5 CFD model computational domain

The region shown was approximately 25.5 m (83.7 ft) in length, 2 m tall (6.5 ft), and 4.7 m (15.4 ft) wide.

The boundary conditions for the model included a velocity inlet condition on the headgate side, thereby controlling the volume of air across the face. The tailgate side was represented with a static pressure boundary condition of zero. The plane where the flooded-bed screen rests was chosen as the boundary for the scrubber inlet. In this way, the influence of the duct design was captured in the calculations. A volumetric flow was assigned to this region. The same magnitude of flow was assigned to the discharge of the centrifugal fan, representing the discharge of the scrubber system through that ductwork. The internal components of the scrubber, such as the flooded-bed screen and demister were not included in the computational domain. The coal on the AFC was given a translating boundary condition to mimic the influence of the moving conveyor. The spalled coal thrown up by the headgate drum was given a rotating wall condition, with the center of rotation at the axis of the drum. This gives that surface the appropriate tangential velocity observed at the mine. The remainder of the surfaces, such as the shearer body, AFC, and supports, were given a stationary wall boundary condition.

Within Cradle, multiple models are available to describe the influence of turbulence. In this study, two models of turbulence were tested: the standard $k-\varepsilon$ model and a variation known as the RNG $k-\varepsilon$ model. The RNG $k-\varepsilon$ model differs from the standard model by adding an additional source term in the transport equation for the rate of kinetic energy dissipation. This allows it to describe the effects of rapid changes in strain rate and streamline curvatures.

In order to ensure that the mesh would not significantly impact the results of the simulation, it was necessary to establish grid independence. This was accomplished through progressive refinement of the size of the grid used in the model. Grid independence was established by monitoring velocity values near the inlet to the scrubber. The number of elements varied from 2.2 million elements to 8.1 million elements, with less than 3% variation observed in those velocity values. In each case, local refinement was required near the inlet and discharge of the scrubber, where high velocity and pressure gradients were present.

Steady state and transient state simulations were conducted at varying flowrates in the model in an attempt to find the optimum ratio between scrubber air volumes and face air volumes. Two different velocities were chosen for the headgate inlet, 2.5 m/s and 3.0 m/s (500 fpm and 600 fpm) and six scrubber flow volumes in equal increments from 3.0 m^3/sec to 6.0 m^3/sec (6,400 cfm to 12,700 cfm). Converged steady state solutions were used to establish the initial conditions for the transient simulation. Convergence was established by monitoring residuals RMS errors to a value less than 10^{-4} and domain mass imbalance to less than 0.1%. To represent dust in the system, 250 marker particles were generated at time zero, t=0.00 seconds, spread over the surface of the spalled coal in the model. The particles were then followed through the model as they are transported by the pattern of air at the faces, while influenced by the dust scrubber. The particles were counted when they reached the surface of the flooded-bed screen and are deemed to have been captured by the scrubber. After 20 seconds, the particles were either captured by the screen, or too far removed from the inlet to be captured. In this way, the *capture efficiency* of the scrubber design was estimated.

4. Results and discussion

A table of capture efficiency has been compiled with different airflows at the face and through the scrubber, as seen in table 1. Reported capture efficiency values have converged to within 0.5% in each case.

Table 1 Dust capture efficiency predicted by CFD simulation for varying scrubber volume flows and face velocities

Predicted Dust Capture Efficiency						
Mean Face Velocity (m/s)	Scrubber Volume (m^3/s)					
	3.0	3.6	4.2	4.8	5.4	6.0
2.5	75.7%	85.1%	76.2%	80.3%	90.8%	88.3%
3	74.6%	81.4%	84.0%	88.8%	90.8%	88.0%

From the table, it is clear that the scrubber and inlet design exhibits promise. It is achieving a 75% to 90% dust capture efficiency over the range of values tested, for dust generated at the headgate drum. As expected, as the volume of air through the scrubber increases, the dust capture efficiency increases, in general. In Figure 6, one can observe the predicted velocity contours along the face. The plane nearest the scrubber inlet exhibits a uniform flow pattern which would discourage mixing of the dust laden air prior to entering the scrubber inlet. This is thought to be the preferred flow pattern in this

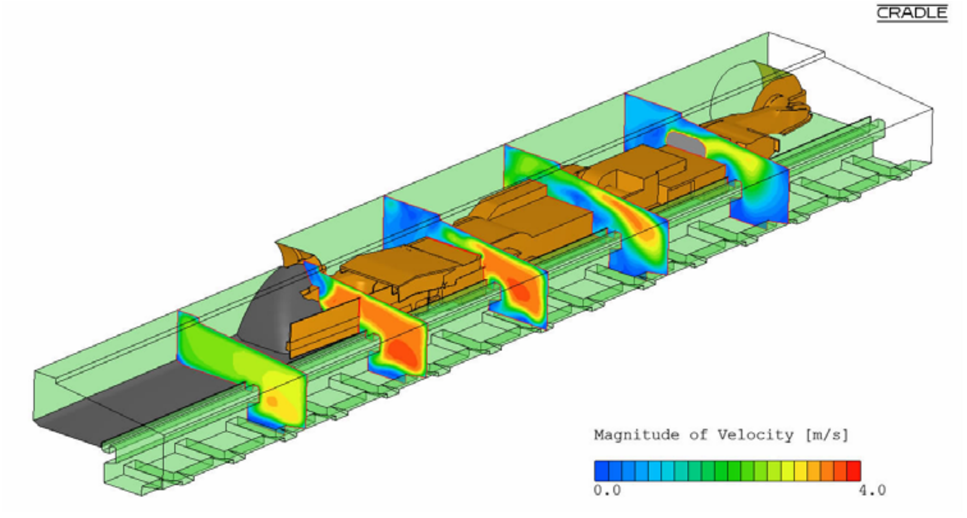

Fig. 6 Predicted velocity contours along the longwall face under the influence of a fan-powered flooded-bed scrubber, at 5.4 m^3/s (11,400 cfm) through the scrubber with a mean face velocity of 2.5 m/s (500 fpm)

region, as the dust laden air should be contained on the face side of the shearer air deflector and away from the miners in the walkway. In these simulations, the spray nozzles have been excluded, in order to concentrate on the impact of the scrubber. Adding the spray nozzles will likely change the results, but the optimum configuration of nozzles with an active scrubber is not known.

5. Ongoing and future work

The following CFD simulations are underway or planned. Individual components of the scrubber system will be characterized, including the flooded-bed and the demister. The discharge of the scrubber system needs to be examined to discover ways to take advantage of this energetic stream of clean air. The configuration of the spray nozzles on the shearer body will be examined in an attempt to optimize this system.

Aside from CFD modeling, a full scale, functional prototype of the scrubber system and a model of the longwall shearer is being built to be tested at the NIOSH facility in Pittsburgh, PA. A 1:20 reduced scale model is also being tested in the laboratory. These experiments are planned in order to validate the design and confirm the potential for this system to reduce dust concentrations at the longwall face and improve the working conditions and health of underground miners.

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