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Scale modeling of dust capture through a flooded-bed dust scrubber integrated within a longwall shearer

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Abstract

Meeting federal dust standards at a longwall mine face is among the more difficult challenges for a longwall mine operator. With recent changes in federal dust regulations requiring lower worker exposure, maintaining compliance has become increasingly difficult. The authors recommend the concept of controlling respirable and float dust, which is inherent in longwall mining, through the application of a flooded-bed dust scrubber to a longwall shearer. A full-scale physical model of a longwall shearer, modified with an integrated flooded-bed scrubber, was designed and fabricated at the University of Kentucky to measure the effects of a flooded-bed scrubber on dust capture at a longwall face. The mockup was transported, assembled, and tested in the longwall dust gallery at the Pittsburgh Research Laboratory of the National Institute for Occupational Safety and Health (NIOSH). Test results indicated a dust reduction of up to 57% in the return airway of the longwall gallery. The test results were validated with Computational Fluid Dynamics (CFD) modeling with a maximum of 9.7% difference in results. The aim of the study was to test the flooded-bed scrubber concept with a longwall shearer on a half-scale model using the CFD modeling technique. The paper discusses the validation of the developed scaling laws through the results of CFD modeling on the full-scale porotype and half-scale model.

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Nomenclature

ΔP	pressure drop (Pa)
l	characteristic length (m)
ρ	air density (kg/m^3)
v	air velocity (m/s)
g	gravitational acceleration (m/s^2)
Q	quantity of air (m^3/s)
F_p	pressure force on airflow (N)
F_i	inertia force of air (N)
F_g	gravitational force on airflow (N)

Introduction

Dust generation in an underground coal mine is an undesirable result of various mining activities, particularly cutting, crushing, and transportation. It is one of the major underground environmental problems faced by mine operators, especially underground longwall mine operators. The problem is more prominent at the working face of a longwall mine where coal is extracted. The coal cutting machine (shearer) generates high concentrations of dust, accounting for over 50% of the total respirable dust generated at the face [1]–[3].

The generated dust, if not captured, becomes airborne and permeates throughout the downwind ventilation airflow. Prolonged exposure to high concentrations of airborne respirable dust (dust particles having an aerodynamic diameter < 10 μm) poses significant health risks to people working in this underground environment; coal workers' pneumoconiosis (CWP), silicosis, emphysema and chronic bronchitis, collectively known as black lung, are

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known examples [4]. After inhalation, the respirable dust particles enter a miner's lungs and contaminate them slowly and insidiously. This continual contamination causes damage to the lungs and can eventually hinder normal respiration/breathing, making the miner progressively unfit to work. In its advanced stages, black lung can lead to permanent disability and death. According to NIOSH, black lung has been a cause or contributing factor in the death of 76,000 miners since 1968 and has cost more than 45 billion dollars in federal compensation benefits [5]. Another report by NIOSH states that the disease killed 10,000 miners between 1995 and 2004 [6].

In addition to being a devastating health issue, mine dust is also a challenging safety issue. A portion of the airborne coal dust advects downwind from the longwall face, and increases dust concentration on the return entries' surfaces. The deposited dust, if inadequately diluted with inert rock dust, typically pulverized limestone, can turn a less-dangerous, localized methane explosion into a catastrophic coal dust explosion [7]. According to MSHA, the Jim Walter No. 5 Mine and the Upper Big Branch Mine disasters, which together killed 42 people, are examples of disastrous coal dust explosions [8]–[10].

Since 1969, several successful efforts have been made to reduce dust concentrations at the working faces of underground mines. The Federal Coal Mine Health and Safety Act of 1969 established dust standards for coal mines that required each underground coal mine to maintain a respirable dust limit at or below 2.0 mg/m^3 in an active working area. This resulted in a decrease in the prevalence of CWP for underground coal miners. However, after a continued period of decline from 1970 to 1995, a rising trend of CWP in the years 1995–2006 prompted the federal government to promulgate more stringent dust regulations [6]. Consequently, in 2010, MSHA proposed a new dust standard that was enacted on August 1, 2014. The new standard requires mine operators to lower the dust-exposure limit from 2.0 mg/m^3 to 1.5 mg/m^3 at the working face [5].

Longwall mines historically had difficulties maintaining dust concentration below the previous dust standard of 2.0 mg/m^3 [11]. After the implementation of the new dust rule, it has become even more challenging for longwall mine operators to meet the permissible requirements while using the same dust control techniques previously employed. Therefore, improvement in current dust control techniques is needed. Borrowing from the successful implementation of flooded-bed scrubbers on continuous miners in room and pillar mines, the authors proposed the integration of this type of scrubber within a longwall shearer for capturing and removing airborne dust generated at a longwall face [12]–[14]. The overall goal was to minimize the amount of airborne dust from migrating from its source.

To test the effectiveness of the concept, the authors designed and fabricated a full-scale physical model (prototype) of a longwall shearer integrated with a flooded-bed scrubber. The prototype was transported and assembled in the longwall test gallery of the NIOSH Pittsburgh Research Laboratory (PRL). Experimental tests were conducted to determine its capture and cleaning efficiencies. The test results were very encouraging and showed dust reductions up to 56.9% in the return airway of the test gallery. A computational fluid dynamics (CFD) study on the prototype indicated a similar result with a 53.6% dust reduction. However, because of several constraints, such as laboratory space, time and costs, it was difficult to experiment with

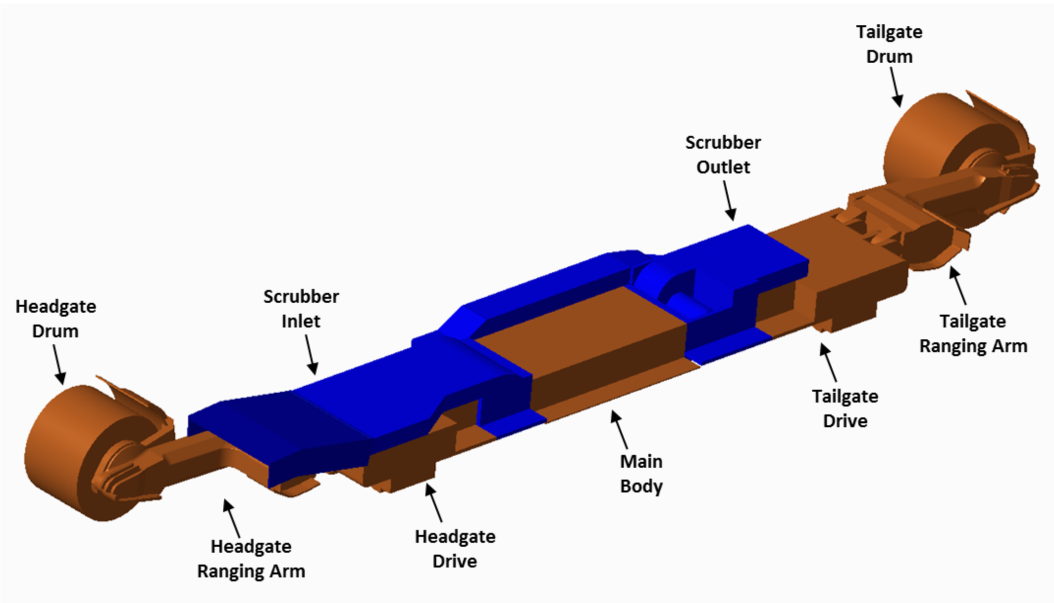

Fig. 1. A 3-D model of the longwall shearer with an integrated flooded-bed scrubber.

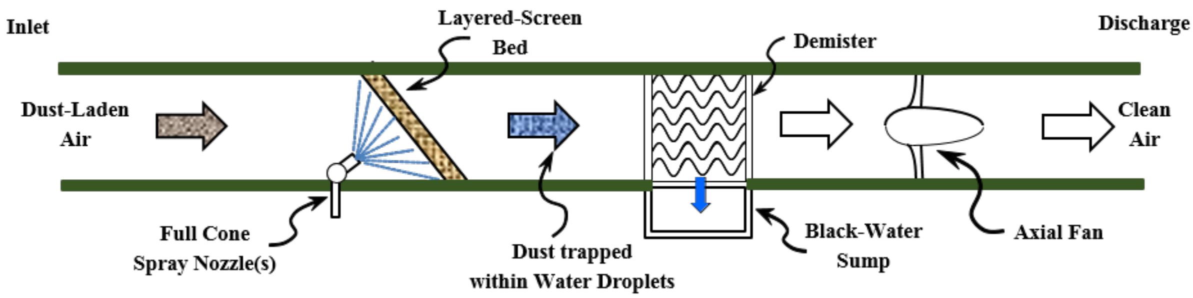

Fig. 2. Representative cross-sectional view of a flooded-bed scrubber.

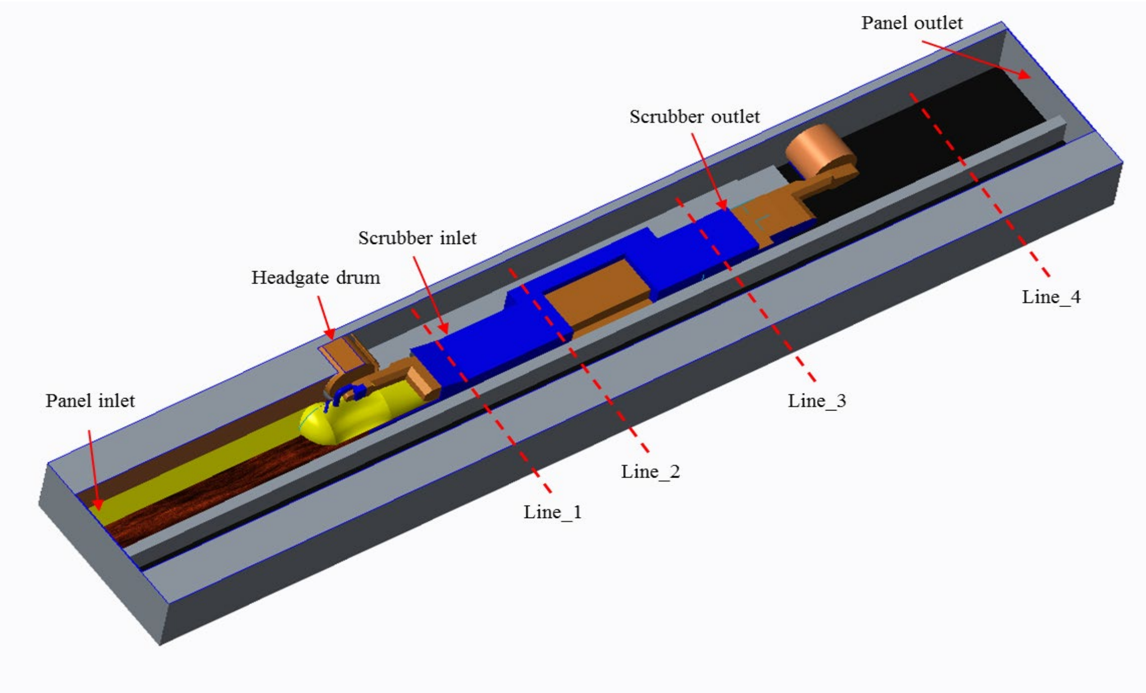

Fig. 3. A 3-D CAD drawing of the PRL longwall test gallery.

scrubber design changes to evaluate their effects on dust capture in the PRL longwall test gallery. This paper examines the possibility of using a half-scale model to investigate the dust capturing phenomenon of the flooded-bed scrubber on the longwall shearer through laboratory experiments and numerical modeling.

Overview of the modified longwall shearer

A 3-D drawing of the modified longwall shearer with an integrated flooded-bed scrubber is shown in Fig. 1. The two shearer drums (cutter bits are not shown in the figure) cut coal from the coal face, which generates dust. However, this study only takes into account dust generated by the cutting action of the headgate drum. Fig. 1 shows the constituent modules of the modified longwall shearer. The blue modules represent the flooded-bed scrubber system proposed for the longwall shearer. The orange portions represent the existing longwall-shearer components.

The flooded-bed scrubber has six main components: an inlet, a full-cone water spray, a wire mesh screen downwind of the spray, a demister downwind of the screen, a dirty water sump under the demister, and a vane axial exhaust fan at the outlet (see details in Fig. 2). During operation, the scrubber exhaust fan creates negative pressure and draws the dust-laden air from the area around the headgate drum into the scrubber's inlet. The dust-laden air then passes through the flooded-bed screen, where the dust particles are entrained in the water droplets created by the water spray. Subsequently, the dust-laden water droplets move downwind from the flooded-bed to the demister. The demister, which consists of parallel sinuous layers of plastic, separates the dust-laden water droplets from the air before the air reaches the fan. The dust-laden water flows down to the sump, where it is pumped onto a conveyor. Finally, the clean and relatively dry air passes through the fan into the downwind ventilation air that flows to a return airway.

Table 1. Full-scale parameters and their corresponding half-scale values.

Scale	Face Velocity (m/s)	Dust Source 1 (m/s)	Dust Source 2 (m/s)	Dust Source 3 (m/s)	Scrubber Quantity (m^3/s)
Full-Scale Prototype	3.048	5	35	30	6.46 & 2.99
Half-Scale Model	2.15	3.53	24.74	21.21	1.14 & 0.53

Experimental set-up

The modified longwall shearer was placed in the PRL longwall test gallery for experimental testing. The PRL longwall test gallery is 38.13 m (125 feet) long and 2.29 m (7.5 feet) high, as shown in Fig. 3. Ventilation of the test gallery is powered by three exhaust fans, connected in parallel, capable of supplying a maximum of 22.20 m3/s of air along the simulated coal face. Keystone Mineral Black 325 BA dust of size ranging from 0.5 to 50.0 µm, with 99% of particles below 3 µm by count, was introduced into the panel through three sources located near the headgate drum. The locations of the dust sources were carefully selected to generate a dust profile similar to that found in a longwall mine.

The full-scale experiment was designed to determine the effects of different factors on the capture and cleaning efficiencies of the scrubber. A two-level factorial design was preferred considering available resources, time and costs. Three factors were studied: the face air velocity, the scrubber air quantity, and the inlet extension (installed and removed). A set of eight experiments were performed. Each experiment was performed in two stages: first, dust concentration was measured in the return airway with the scrubber turned OFF; then the dust concentration was measured at the same location with the scrubber turned ON. The percentage of dust captured and cleaned by the scrubber was calculated by dividing the dust concentration with scrubber ON by the dust concentration with scrubber OFF. However, for the half-scale modeling, only the effect of scrubber air quantity was studied. The face air velocity and the inlet were kept at their high levels. This resulted in a total of two experiments with two different scrubber quantities. CFD simulations for both the full-scale prototype and the half-scale model were performed for two different scrubber quantities, and the results were compared for validating the derived scaling laws.

Scale modeling

Scale modeling is a technique used to achieve a high degree of similarities, generally with the geometry and physical phenomena, between a fractional-scale model and a full-scale model (in this case the prototype) [15], [16]. It allows one to establish a scaling relationship between the characteristic length of the scale and different physical quantities using physical laws governing the phenomena. Consequently, it can be very helpful and economical in predicting the results for the full-scale prototype using the scale model results [15], [17], [18].

The airflow in the system is governed mainly by inertial force (F_i), pressure force (F_p), and gravitational force (F_g). Since the Reynolds number (Re) of the fluid (air) in the system is very high ($Re > 10^5$) and the flow pattern is fully turbulent, the viscous forces are considered insignificant compared to the inertial force. Furthermore, since the dust particles are very small in size (< 3µm) and light in mass, they are considered as air particles. Therefore, the governing forces can be defined as follows:

$$F_p = \Delta P l^2 \quad (1)$$

$$F_i = \rho l^2 v^2 \quad (2)$$

$$F_g = \rho l^3 g \quad (3)$$

From equations (1), (2), and (3), two pi-numbers, Euler number, and Froude number, can be formed.

π_1 = *Euler Number* (E_u) = $F_p/F_i = \Delta P/\rho v^2$

Since the fluid (air) in the full-scale and half-scale models are the same,

$\rho_{Full} = \rho_{Half}$

$$\pi_1 = \Delta P/v^2 \quad (4)$$

π_2 = *Froude Number* (F_r) = $F_i/F_g = v^2/lg$

$g_{Full} = g_{Half}$

$$\pi_2 = v^2/l \quad (5)$$

Therefore

$$v \ \alpha \ \sqrt{l} \quad (6)$$

and

$$Q \ \alpha \ l^{2.5} \quad (7)$$

Using equations (6) and (7) and the full-scale numerical model input values, half-scale numerical model input values are calculated, as shown in Table 1.

Table 2. Comparison of experimental and numerical results of the scrubber dust capture efficiency.

Scrubber Quantity (m^3/s)	Experimental (%)	Numerical Simulation (%)	Difference (%)
6.46	56.99	53.63	5.89
2.99	33.19	30.89	6.94

Because the capture efficiency itself is a dimensionless number, it can serve as an important pi-number to measure the performance of the flooded-bed scrubber. Therefore,

$$\pi_3 = \textit{Scrubber Capture Efficiency} = \textit{Constant} \quad (8)$$

The third pi-number indicates that the capture efficiencies of the full-scale prototype and the half-scale model should be the same.

CFD modeling

CFD modeling is a powerful tool for numerically solving complex fluid dynamics problems. It is used extensively to predict, optimize, and verify the performance of a design [19], [20]. The CFD modeling technique was used for this study to reconstruct the dust capture by the flooded-bed-scrubber experiment performed on the full-scale model at the PRL. First, a CFD simulation was performed for the full-scale prototype to compare and validate the numerical results with the experimental results. A CFD simulation was then performed for the half-scale model to compare the full-scale simulation results with those of the half-scale model and to verify the validity of the derived scaling laws.

Cradle SC/Tetra V12 CFD software, which is used for thermo-fluid analysis, was employed for this study. The CFD simulation was performed in two steps: single-phase, steady-state simulations for the airflow representing conditions before dust release, and transient-state simulations for the dust capture by the flooded-bed scrubber, representing the condition after dust release. The geometry of the longwall test gallery was generated using a computer-aided design (CAD) package, PTC Creo (Fig. 3). The 3-D rendition includes nearly all the features of the gallery, except for some minor details, which are removed to reduce computational time. All the simulations were performed with double precision on a Windows workstation having two 12-core, 3.0-GHz, Intel microprocessors and 128 GB of memory.

The flow in the computational domain was assumed to be incompressible. Turbulence was modeled with the Reynolds Averaged Navier-Stokes equations (RANS) with the Standard K-ε turbulence model. Analysis conditions for the steady-state simulation included: fixed air velocity at the panel inlet, fixed air velocity at the three dust sources, fixed negative volumetric flow at the scrubber inlet, fixed positive volumetric flow at the fan outlet, and zero static pressure at the panel outlet. All boundary walls were treated as smooth and stationary, except the headgate drum, which was assigned a rotating wall condition to represent a rotating drum during the cutting operation.

Unstructured tetrahedral computational mesh was generated in the computational domain using the finite volume method. Prism layers were used on wall boundaries to ensure high numerical accuracy. To ensure that the CFD results do not depend on the mesh and to explain the physics with utmost accuracy, grid independence studies were carried out for both the full-scale prototype and the half-scale model. Based on the results of these studies, 13.1 million and 7.0 million elements were used for the prototype and scale model, respectively.

Mass and momentum conservation equations were used as governing equations to obtain velocity and pressure fields. The steady-state solution was assumed to converge when the average residuals of all the variables were less than 10^{-5} within a cycle, and mass flow was balanced. The time-step for the transient analysis was kept very low to keep the average courant number below 1. The particle tracking approach was used to simulate the interaction between the dust particles and fluid, and to study the motion of the dust particles in the panel. Particle tracking uses the Lagrangian equation of conservation to track the trajectory of the particles or clusters of particles through the computational domain [19].

Mass particles of different sizes varying from 0.5 μm to 3.0 μm, in a proportion measured during the sampling of original dust, were continuously generated (350 particles every 0.4 ms) from the three dust sources. A portion of the particles moved into the scrubber under the influence of negative pressure generated by the scrubber fan, and the remaining particles traveled to the return. The transient-state simulation was run until the number of particles moving into the scrubber was constant with time and achieved a saturation state. The number of particles drawn into the scrubber divided by the total number of particle generated, during the saturation state, defined the capture efficiency of the scrubber. Validation of numerical results with experimental results of the scrubber dust capture efficiency at different scrubber air quantities is presented in Table 2. The percentage difference was calculated by dividing the difference between the experimental and numerical results by the experimental result. The numerical results are in good

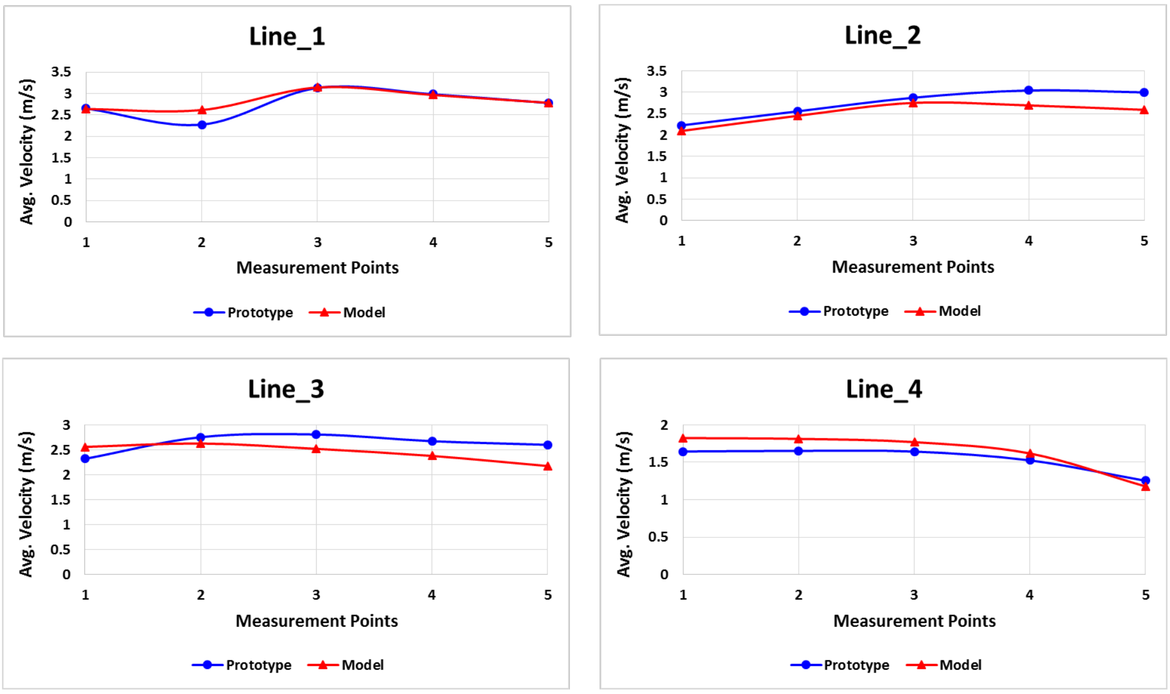

Fig. 4. Comparison of velocity profile measured at four cross-sections of the longwall test gallery.

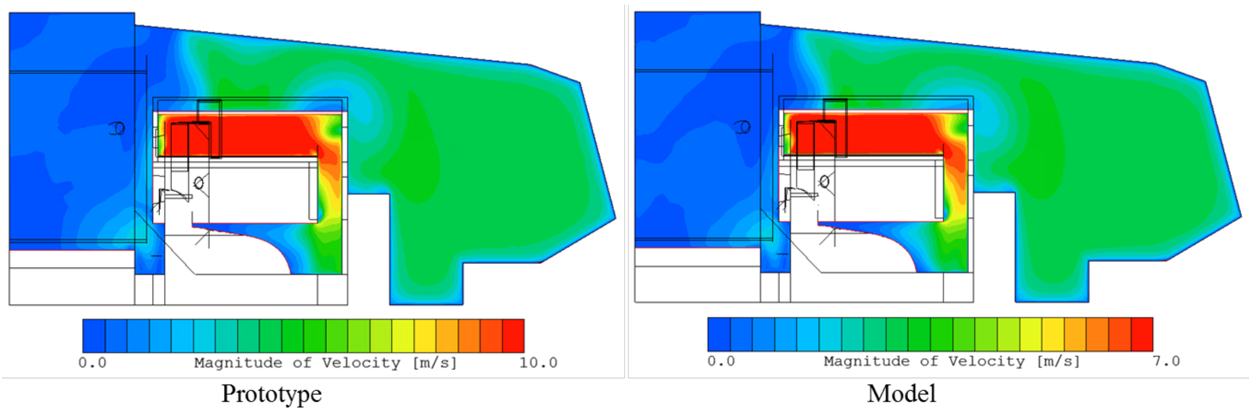

Fig. 5. Velocity gradient at a cross-section 12 m from the inlet.

agreement with experimental results, with a maximum 6.94% variation.

Results and discussion

The magnitudes of average velocity at 20 different points in the computational domain were measured using the CFD simulation results from the full-scale prototype and the half-scale model. The measurement points were positioned on four straight lines (each having five points) located 2.2 m above the ground and 12 m, 15 m, 21 m, and 30 m from the inlet, as shown in Fig. 3. The comparisons of average velocities are presented in Fig. 4. In order to better compare the results, the magnitude of average velocity for the full-scale prototype is reduced by a factor of root square of the scale ratio (0.5) at the 20 measuring points. Fig. 4 shows a similar airflow pattern for the two scales at the four lines, with a small variation, which further indicates that the whole computational domain has similar flow patterns. This validates the scaling laws for air velocity in the computational domain.

Comparisons of velocity gradients between the full-scale prototype and the half-scale model at two cross-sections located 12 m and 21 m from the inlet are shown in Fig. 5 and Fig. 6, respectively. The velocity range for the full-scale prototype is 0–10 m/s, whereas the velocity range for the half-scale model is reduced by a factor of root square of the scale ratio (0.5) considering the validity of airflow scaling laws. The results suggest matching patterns for the two scales with small variations.

The Euler Numbers calculated from the pressure drop across the test gallery and the inlet air velocity for the full-scale prototype and half-scale model are found

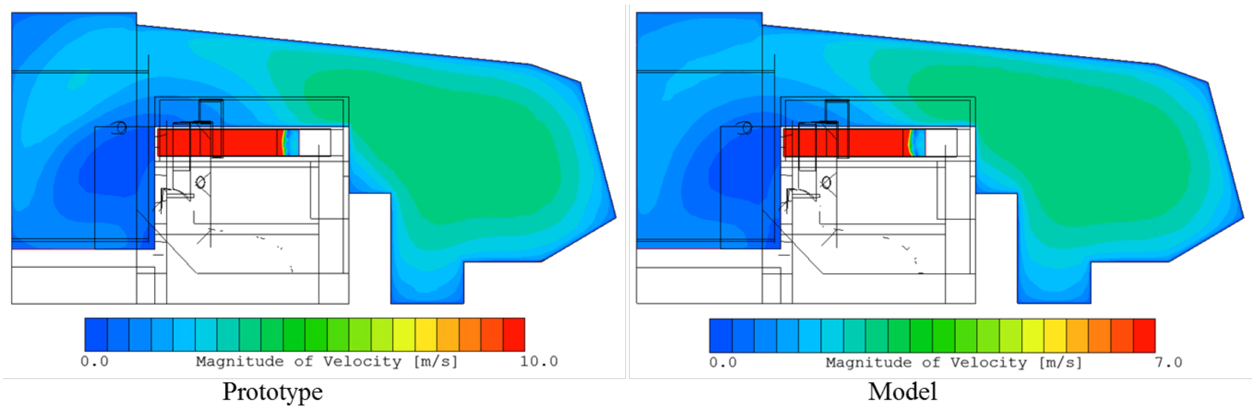

Fig. 6. Velocity gradient at a cross-section 21 m from the inlet.

Table 3. Euler number calculation for the full-scale prototype and half-scale model.

	Prototype	Model
Velocity (m/s)	3.048	2.15
Pressure Drop (Pa)	29.81	15.00
Euler Number	3.20	3.24

Table 4. Comparison of full-scale prototype and half-scale model results of the scrubber dust capture efficiency.

Scrubber Quantity (m^3/s)	Prototype	Model	Difference (%)
6.46	53.63	51.62	3.75
2.99	30.89	28.24	8.58

to be constant, as presented in Table 3.

Results of the flooded-bed-scrubber dust-capture efficiencies are presented in Table 4. The percentage difference of capture efficiencies between the full-scale prototype and half-scale model at high and low scrubber capacities are 3.7% and 8.5%, respectively. This indicates acceptable agreement with the derived scaling laws, which predicts the same capture efficiencies for the two scales.

Conclusions

Underground longwall mining in the United States has many challenges, and dust control is one of the most significant among them. The application of a flooded-bed scrubber within a longwall shearer can be very useful to reduce dust concentrations at a longwall face. It has significant potential to enhance the health and safety of underground miners. To test this concept, a full-scale prototype of a longwall shearer with an integrated flooded-bed scrubber was built at the University of Kentucky and tested in the NIOSH Pittsburgh Research Laboratory. Test results showed up to a 57% dust reduction in the return airway of the dust gallery. The test results validated numerical simulations with a maximum of 9.7% variation. To increase the ease at which future studies can be performed and to reduce the costs of experimenting with potential design changes, the use of scale modeling in the computational domain is proposed.

This study was conducted to investigate the use of a small scale model to predict the results for the full-scale prototype using scaling laws. CFD simulations for the scale model were performed, and results were compared with the prototype CFD results. The analysis of results shows similar velocity profiles and dust capture efficiencies, which validates the derived scaling laws.

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