

Investigation of explosion hazard in longwall coal mines by combining CFD with 1/40th scaled physical modeling

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ABSTRACT: To evaluate methane explosion hazards in longwall coal mines, researchers at the Colorado School of Mines have developed a Computational Fluid Dynamics (CFD) model, along with a 1/40th scaled, optically accessible model of an underground longwall mining section. In this project, CFD models assisted in the design of the physical model to ensure specifications were met for accurately representing the scaling physics as well as assist in narrowing the experimental matrix and identifying key locations for sensor placement to measure, flow, pressure, and gas concentrations. This procedure will help develop a mine wide methane monitoring system to improve methane ignition and explosion mitigation strategies in longwall coal operation.

1 INTRODUCTION

Adequate ventilation and mine atmospheric monitoring system are keys in preventing explosions in underground coal operations. A major concern in longwall coal operations is methane gas explosions in the face area that could potentially transition to a more severe coal dust explosion, such as the Upper Big Branch (UBB) mine explosion in 2010 (Page, 2011; Phillips, 2012). Explosion risks always exist in longwall operation, primarily in the form of face ignitions in the longwall face and gob areas.

Several factors, such as ventilation setup and gob characteristics, can significantly impact the formation of explosive gas mixtures inside the longwall face and gob area. The use of point-type methane sensors to detect the explosion risk relies heavily on the sensor placement (Juganda, 2020; Krog, 2016). In addition, due to its inaccessibility, methane monitoring of the gob area is difficult. Mine operators usually rely on methane drainage through Gob Ventilation Boreholes (GVB) and nitrogen injection as a preventive method. These methods are commonly used for progressively sealed gobs, but nitrogen injection is less effective for bleeder-ventilation panels (Marts et al., 2015; Saki, 2015).

Researchers at the Colorado School of Mines (CSM) have built a 1/40th scaled physical model of a longwall coal mine. To complement and guide the development of this model, Computational Fluid Dynamics (CFD) modeling is used to help identify critical ventilation parameters, such as flow scaling, gas mixture distribution, and sensor placement. These parameters are first optimized in the CFD model, then implemented in the scaled physical model. The physical experiments are used to validate the CFD model, including gob permeability. The validated CFD model can help reduce the time and number of experiments required for different ventilation scenarios.

The combination of Computational Fluid Dynamics (CFD) and scaled physical modeling can be used to develop more reliable atmospheric monitoring practices and provide an improved understanding of the gas mixtures formation inside the gob for different ventilation

scenarios. The goal of this project is to develop early detection method to improve methane explosion prevention and mitigation strategies in longwall coal operation.

2 PHYSICAL MODEL OVERVIEW

The 1/40th scaled physical model has a dimension of 7 m long by 6 m wide and 1.7 m high. The modeled active longwall panel includes the longwall face, gob area, the surrounding mine entries, and the ventilation control required to simulate different ventilation setup. The scaled version has optical access on the sides and tops to visually observe the airflow pattern. Flow and gas sensors are installed in critical areas to analyze the flow distribution and gas mixtures inside the gob area and surrounding mine entries. The mine entries dimensions are 144.8 mm wide and 72.4 mm high, which are equivalent to 5.8 m wide and 2.9 m high in full scale.

The longwall face is 5.5 m long, equivalent to 220 m in full scale, and separated into 11 face carts consisting of 10 shields per cart. These face carts can be advanced individually to simulate different shearer cutting scenarios. Automation is integrated into the shearer using a Bluetooth connection to allow movement across the face, and adjustment to each shearer arm height and drums rotation depending on the simulated scenario (McMack et al., 2018, Pinheiro et al., 2020).

The gob cart dimension is 60 cm long, 50 cm wide, and 61 cm high. The model can accommodate 11 columns and up to 6 rows of gob carts. Each gob cart can be filled with different ball sizes to simulate the different gob porosity and permeability distribution observed in the real longwall gob. Figure 1 shows the schematic of the physical scaled model, while Figure 2 shows the picture of the built model.

The model allows methane inflow into the model through two injection systems. Figure 2 (right) shows the gas injection manifold at the face carts that will be connected to the injection

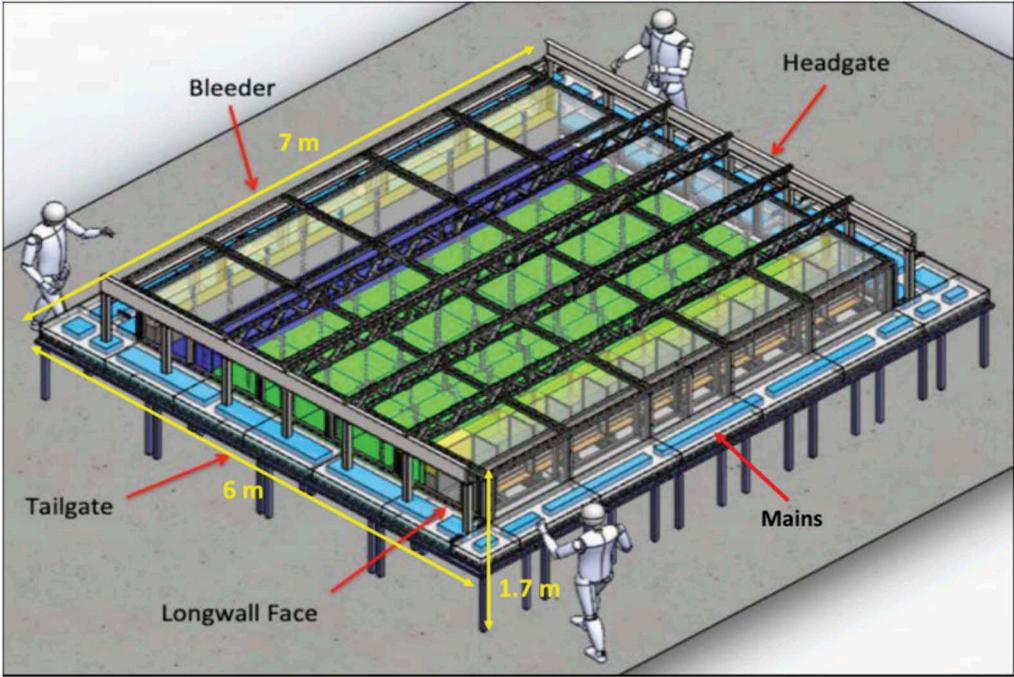


Figure 1. Isometric view of the 1/40th scaled physical longwall model schematic. (Modified from McMack et al., 2018).

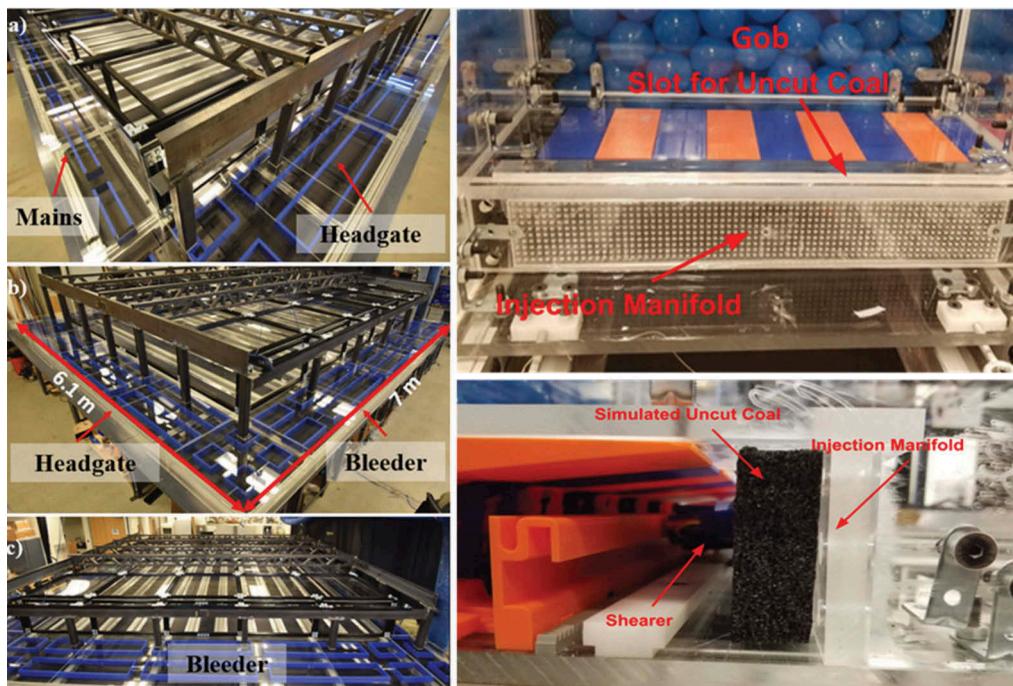


Figure 2. Left (a), (b), (c): Assembled physical scaled model (Pinheiro et al., 2020). Right: Longwall face injection system.

line. These manifolds consist of 6 mm diameter holes spaced every 6 mm. Behind the manifold, 25 mm thick porous foam is used to simulate the uncut coal that also diffuses the incoming simulated methane. Due to safety concern, 70%He/30%CO₂ gas mixtures, which has similar molecular weight with pure methane gas, is used to simulate methane in the physical model. The second injection system, shown in Figure 3, is located on top of the model and used to deliver the simulated methane inflow from the fractured strata above the gob. The gas lines are 12.7 mm in diameter and each injection point to the gob contains a needle valve to allow gas inflow adjustment. Two flow sensors and a CO₂ gas sensor are installed on six the gob carts to analyze flow and CO₂ distribution inside the gob area. The location of these six gob carts is interchangeable with other gob cart to analyze different part of the gob. Several more flow and CO₂ sensors are installed on the longwall face and mine entries.

3 CFD MODEL

ANSYS Fluent v. 18.2 is used for the CFD simulation. The CFD model is developed based on the scaled physical model dimensions and features, such as adjustable face carts, gob carts, and ventilation controls. The model is separated into multiple segments and meshed separately before combining them in the ANSYS Fluent software for the simulation. The model is separated as follows:

- Longwall face consists of 11 face carts, 110 shields, armored face conveyor, and a shearer, which have been simplified compared to the physical model.
- Mine entries and ventilation control, such as stoppings and regulators
- Gob carts, consists of front gob, back gob, and middle gob with adjustable gob rows
- Strata gas injection system consists of the gas injection system and strata

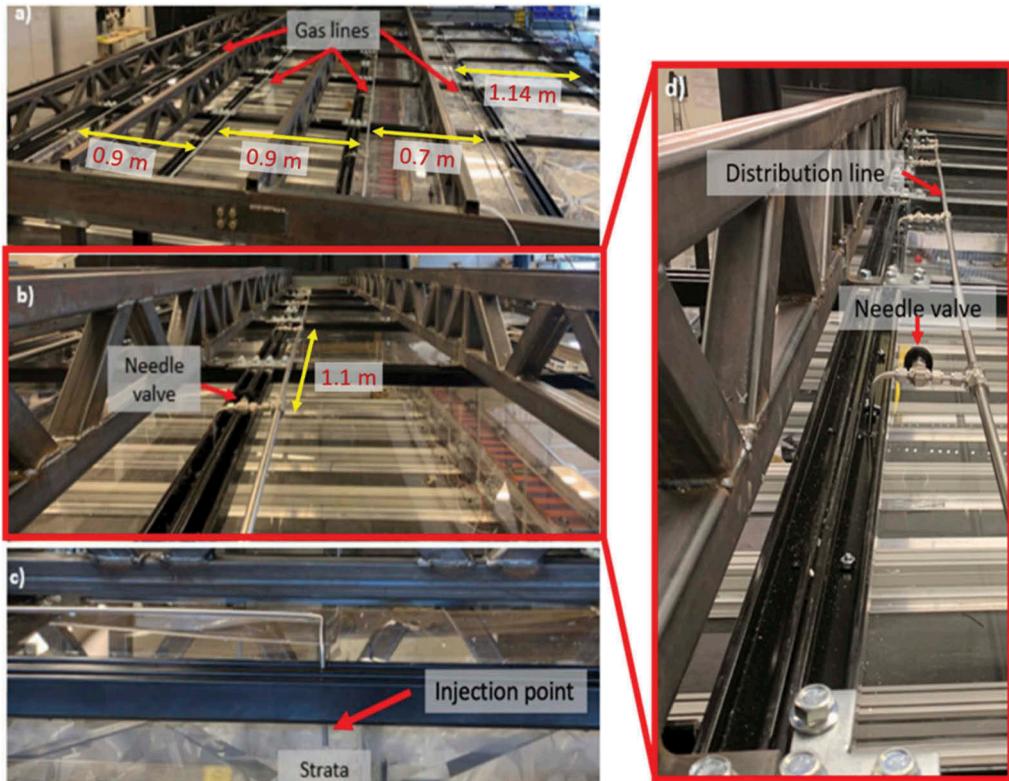


Figure 3. Strata simulated methane gas injection system. a) overview of the gas system. b) and d) close-up view of a single distribution line. c) close-up view of an injection point into the strata.

Figure 4 shows an example of the model geometry separation for meshing purposes. The arrows indicate the interface connection once the model is assembled in the Fluent software.

In the physical scaled model, a porous foam will be used to represent the uncut coal, as shown earlier in Figure 2 (right). In the CFD model, the uncut coal is modeled as a porous medium with a source term assigned to supply a certain amount of simulated methane into

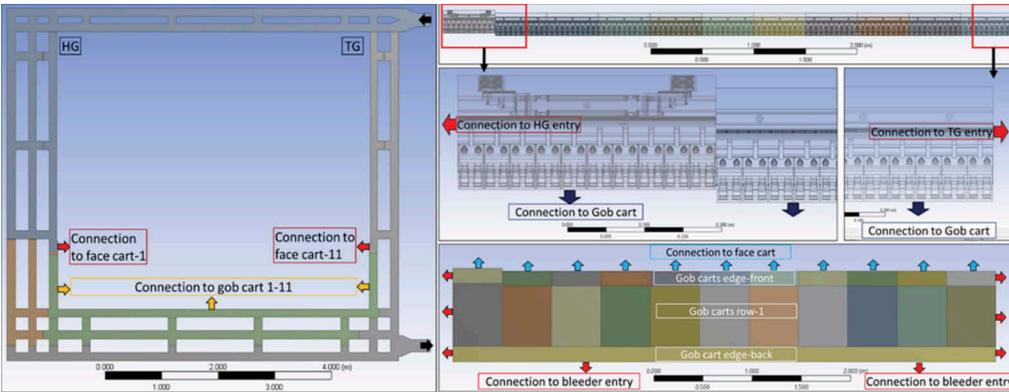


Figure 4. Model geometry separation- Mine Entries (left), Longwall face (top right), and gob (bottom right).

the longwall face area. The gob and strata height can be adjusted within the 61 cm available space inside the model. The strata injection system can also be adjusted to deliver the methane gas either to the top of strata, or directly into the top of the gob. In the physical model, porous foam is used to represent the strata. In the CFD model, a porous zone with adjustable viscous resistance is used to model the strata.

Figure 5 (left) shows a close-up view of the longwall face area and porous zone that represents the uncut coal, while Figure 5 (right) shows the strata injection system.

Depending on the focus area of the study, certain sections of the model will be re-meshed to refine the area of interest. For example, if the focus of the study is to analyze flow pattern and gas distribution in the longwall face area, the longwall face cart mesh will be refined and the strata injection system will be simplified to reduce the computational time. Table 1 shows the mesh summary for the CFD model with the gob modeled as a porous medium.

The model can be re-assembled to simulate different gob sizes and ventilation scenarios, as shown in Figure 6.

The following assumptions are currently used for the CFD model, and will be refined as more data becomes available from the experiments in the scaled physical model:

- The stopping is modeled as a porous medium with an adjustable viscous resistance value of $1 \times 10^{13} / \text{m}^2$, used to represent stopping with minimal leakage. It can be changed to solid objects to represent a seal in U-type ventilation.
- The regulators are modeled as a porous medium with adjusted viscous resistance value to reduce mesh requirement the computation effort of having to redraw the model each time to adjust the flow. The viscous resistance value for each regulator is adjusted to match the flow passing through the regulator in the physical model for the tested ventilation scenario.
- The gob and strata zone are modeled as a porous medium with adjusted viscous resistance. For a detailed study on a specific part of the gob, partial discrete gob modeling can be done by replacing one or more gob carts with a discrete model.

Table 2 shows the model settings used for the simulation.

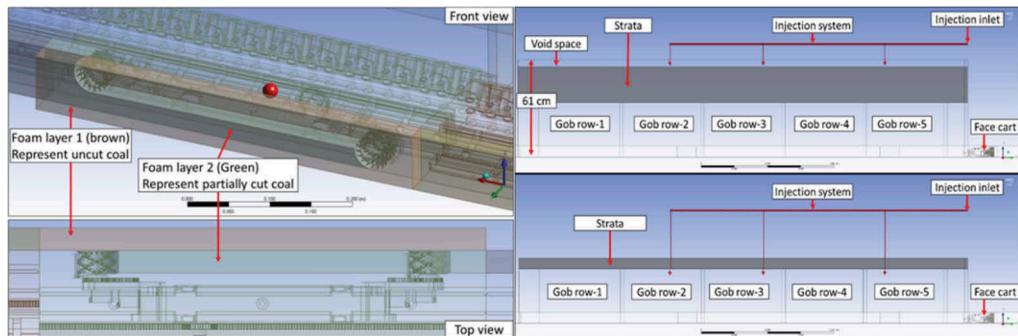


Figure 5. Geometry showing a porous medium that represents uncut coal (left) and cross-section view of the strata injection system (right).

Table 1. Mesh summary.

Segment	Cell size	Mesh control	Cell number
Mine entries	2 – 16 mm	6 mm for stoppings and regulators	2.4 million
Face carts	1 – 15 mm	5 mm for coal face	7.5 million
Uncut coal face- 11 carts	5 – 15 mm	5 mm for connection with face cart	40,000
Gob carts (for one row)	5 – 20 mm	5 mm for interface with face carts	4 million
Strata + injection system	0.75 – 24 mm	3 inflation layers for injection line	6.6 million

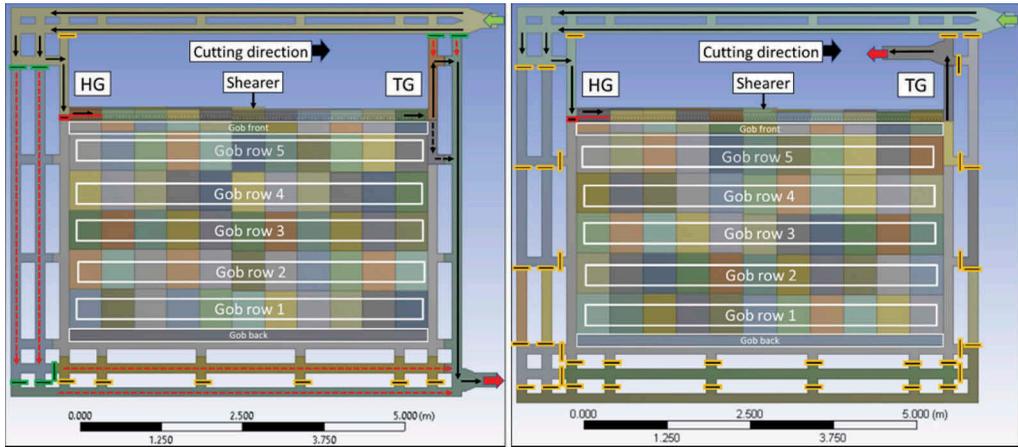


Figure 6. Schematic of 5 rows gob for a bleeder (left) and progressive sealed (right) ventilation system. The red line represents face curtain extending across the first face cart, while the green and yellow colored rectangle represent regulators and stoppings, respectively.

Table 2. ANSYS model setting for CFD simulation.

Parameter	Setting
Time	Steady-state
Solver	Pressure based
Flow density	Incompressible
Species transport	Methane – Air mixtures and simulated methane (He/CO ₂)
Turbulent model	Realizable k-ε with standard wall function
Solution methods	SIMPLE scheme with second-order discretization
Convergence Residuals	1 x 10 ⁻⁴ for continuity and momentum, 3 x 10 ⁻⁵ for turbulence, 1 x 10 ⁻⁵ for gas species, and 1 x 10 ⁻⁶ for energy
Boundary condition	Mass flow inlet and Pressure outlet
Porous zone	Gob, strata, and uncut coal face
Operating condition	Pressure: 80,560 Pa; Temperature: 297 K

4 CFD SIMULATION OF METHANE DISTRIBUTION

For the model setup, mass flow inlet boundary condition is used for the inlets at mains and strata injection line, while pressure outlet boundary is used for the model outlet at the bleeder. The main inlet provides 0.11 m³/s of fresh air. The amount of 100% CH₄ gas supplied from the strata injection lines is set to 0.0011 m³/s, which is approximately 1% volume of the fresh air supplied from the main inlet. An additional 0.0011 m³/s methane gas quantity is set to be supplied from the uncut coal face in a uniform manner, which results in 0.0022 m³/s total methane flow into the model. The modeled gob height is 30.5 cm, while the strata is 7.6 cm high. Both the gob and strata are modeled as porous medium zones. For the gob resistance, the gob edge resistance is assigned a viscous resistance value of 6.5 x 10⁶/m², while a viscous resistance value of 1.05 x 10⁷/m² is assigned to the 5 rows of gob in the middle. These viscous resistance values are based on the physical test done with 58 mm and 38 mm diameter balls packed in random manners. Different gob resistance values will be tested to check the trend. The strata is assigned a viscous resistance value of 1 x 10⁸/m², which is based on a test done on foam material used to represent strata in the physical scaled model.

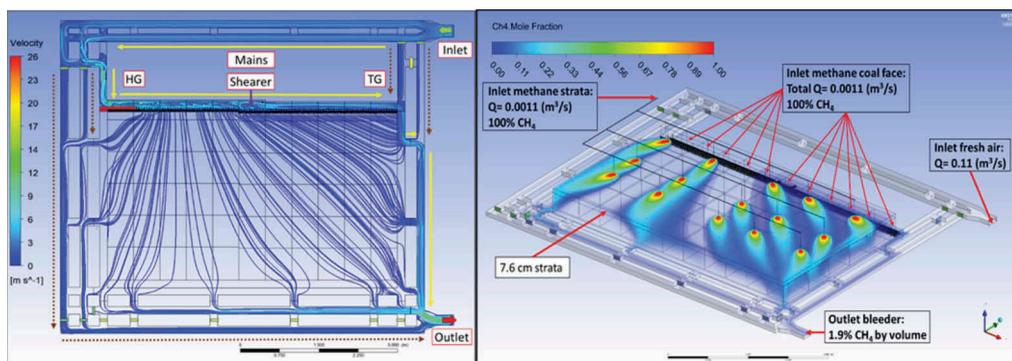


Figure 7. Velocity streamlines (left) showing flow distribution for bleeder ventilation model, only showing the path of fresh air supplied from the main inlet. Red line represents the face curtain extending across the first face cart, while the green and yellow colored rectangle represent regulators and stoppings, respectively. Volume rendering of methane mole fraction (right).

Figure 7 (left) shows the streamlines of methane from the injection pipes colored by methane mass fraction, while Figure 7 (right) shows the methane distribution inside the model in the longwall face and in the gob and strata region.

The results show that continuous leakage occurs across the longwall face as the airflow travels from the headgate to the tailgate side of the face. Parametric study varying flow rate from the main inlet and gob resistance show different leakage rates across the face ranging from 40% - 80% leakage. This leakage rate is within the expected leakage rate typically observed in the real mine, which is around 50% (Krog, 2016) or up to 70% Thakur (2006). Other factors such as gob resistance can also significantly affect the leakage rate, which will be tested using both the physical and CFD models. Some of this leaked air re-enters the bleeder entries through the crosscuts inby the face on both side of the gob, while the rest travel to the back of the gob, which is the typical flow pattern in bleeder ventilation system (Juganda, 2020; Gangrade et al. 2019).

Methane distribution in the model, Figure 7 (right), shows a high concentration of methane on the strata and top part of the gob, where the methane is injected. Most of the methane in the lower gob area, especially on the headgate side, has been diluted and swept by the fresh air leaking from the longwall face, while accumulation at lower concentration can still be seen on the tailgate side of the gob.

5 CFD SIMULATIONS OF SIMULATED METHANE

Injecting a large volume of methane gas into the physical scaled model can create a safety hazard. As an alternative solution, the methane gas is replaced with a non-explosive gas mixture when conducting experiments to analyze airflow distribution and simulated explosive gas concentrations inside the gob and longwall face. An important parameter that requires verification, is the behavior of the alternative non-explosive gas transport compared to the methane gas when used in the physical model. As the methane replacement, a 70%He/30%CO₂ gas mixture was chosen due to having a similar molecular weight (16 g/mol) with pure methane gas. The simulated methane gas transport was investigated using the CFD model and the results are shown in Figure 8 and Figure 9. Note that although the strata were simulated, for visual clarity the methane in the strata is not included in the volume rendering to emphasize the gas distribution inside the gob area where the gas sensor will be installed. The methane concentration in the strata zone can be seen in Figure 7 (right).

The results with the 70%He/30%CO₂ show a similar gas distribution trend inside the gob and longwall face area, especially where the shearer is located, when 100% methane is injected

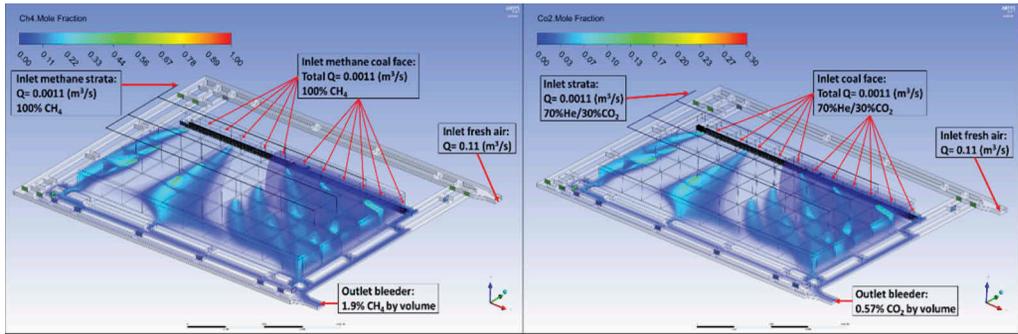


Figure 8. Comparison of CH₄ (left) and CO₂ (right) distribution for 70% He/30% CO₂ simulated methane.

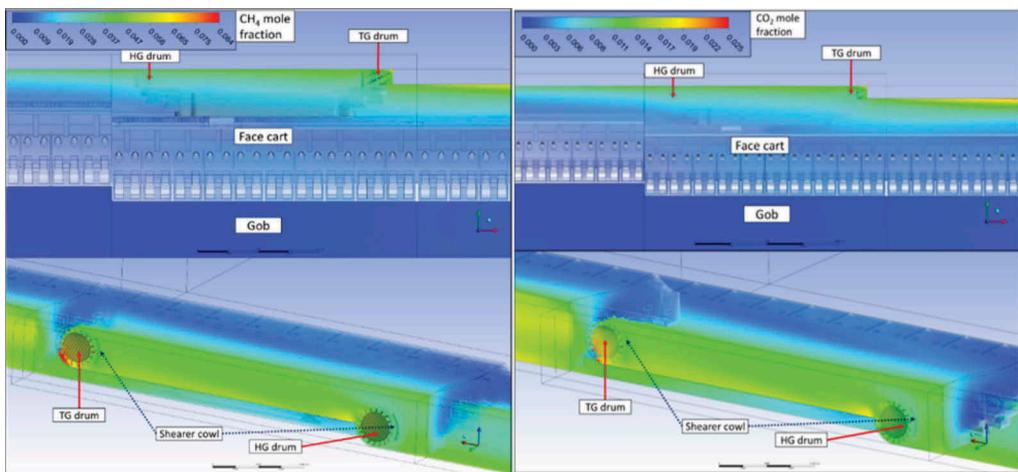


Figure 9. Close-up view of longwall face area showing volume rendering of CH₄ (left) and CO₂ (right).

into the model. Since 70%He/30%CO₂ gas mixture has approximately similar molecular weight with 100% CH₄ gas, the equivalent carbon dioxide concentration by volume should be approximately 30% of the methane concentration by volume, which is shown by the predicted 1.9% CH₄ and the equivalent 0.57% CO₂ reported at the model outlet in Figure 8. Looking at the methane concentration, the area of concern in the longwall face section is around the tailgate corner. As methane continues to accumulate across the longwall face, the highest methane concentration can be found in the last face cart at the tailgate corner. With the current ventilation scenario and shearer located in the middle of the longwall face (face cart-6), Figure 9 shows methane concentration within the explosive range, ~5 – 15% CH₄ by volume, forming around the shearer tailgate drum. The volume of this explosive gas zone is expected to increase as the shearer travel towards the tailgate. The methane distribution inside the gob shows that the leaked fresh air from the longwall face seems to be sufficient to dilute the methane in the headgate side of the gob. However, high concentration of methane can be observed around the top and edges of the gob, along within some crosscuts on the back corner of the gob.

This flow pattern and gas distribution will be verified using the physical model. Different airflow scaling can significantly change the overall methane distribution inside the gob and longwall face area. For this project, the flow scaling was done using geometric, kinematic, and dynamic scaling based on Reynolds number for the flow inside the face area (McMack et al., 2018).

These initial model results indicate the viability of replacing the methane gas with 70%He/30%CO₂ gas mixtures for safety reasons. Instead of CH₄ sensors, CO₂ sensors are installed in the physical model, and the equivalent CH₄ concentration can be calculated from the CO₂ readings.

6 CONCLUSIONS AND FUTURE WORK

A CFD model is used to aid in the design and development of a 1/40th scaled physical model of a longwall coal mine. Simulation results are used to check critical sensor placement locations and the viability of using other gases to simulate methane.

The applicability of the modeling technique and assumption used in the current CFD model, such as modeling gob as a porous medium, is currently being investigated along with modeling the gob as discrete obstacles. Following the physical experiments using the physical scaled model, the resulting airflow pattern, leakage rate, and gas distribution will be used to validate the CFD model. Once validated, the CFD model can be used for parametric studies to check critical parameters and reduce the time and cost required to run physical experiments. This coupled modeling approach can be used to be scaled up to develop more robust full-scale longwall coal mine CFD models that aid in the improvements of ventilation and monitoring practices to reduce the risk of longwall mine explosions.

For future work, the CFD model can be used to simulate different ignition scenarios, such as face ignition by the shearer cutting drum or in-gob ignition behind the longwall shields. Different gob modeling methods, such as partial or full discrete gob modeling (Juganda et al., 2020), can be incorporated into the CFD model for more accurate gob representation in the physical scaled model and allow in-gob ignition simulation.

ACKNOWLEDGEMENT

This research was conducted with financial support by the National Institute for Occupational Safety and Health (NIOSH) under contract number 200-2017-94491, and the use of Colorado School of Mines Wendian High Performance Computers.

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PROCEEDINGS OF THE 18TH NORTH AMERICAN MINE VENTILATION SYMPOSIUM
(NAMVS 2021), JUNE 12-17, 2021, RAPID CITY, SOUTH DAKOTA, USA

Mine Ventilation

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CRC Press

Taylor & Francis Group

Boca Raton London New York

CRC Press is an imprint of the
Taylor & Francis Group, an **informa** business

A BALKEMA BOOK

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Typeset by Integra Software Services Pvt. Ltd., Pondicherry, India

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Library of Congress Cataloging-in-Publication Data

A catalog record has been requested for this book

Published by: CRC Press/Balkema

Schipholweg 107C, 2316 XC Leiden, The Netherlands

e-mail: enquiries@taylorandfrancis.com

www.routledge.com – www.taylorandfrancis.com

ISBN: 978-1-032-03679-3 (Hbk)

ISBN: 978-1-032-03681-6 (Pbk)

ISBN: 978-1-003-18847-6 (eBook)

DOI: 10.1201/9781003188476