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Investigation of Explosion Hazard in Longwall Coal Mines by Combining CFD with a 1/40th-Scale Physical Model

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Abstract
To evaluate methane explosion hazards in longwall coal mines, a CFD model was developed along with a 1/40th-scale, optically accessible model of an underground longwall coal 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 to assist in narrowing the experimental matrix and identifying key locations for sensor placement to measure velocity, pressure, and gas concentrations. This research will help develop strategies for methane monitoring that prevent methane ignitions and explosions in longwall coal operations.

Keywords Longwall · Coal mining · Mine ventilation · Methane · Computational fluid dynamics · Scaled modeling

1 Introduction

Adequate ventilation and a mine-wide atmospheric monitoring system are keys in preventing explosions in underground coal operations. A major concern in longwall coal operations is methane explosions in the face area. Initial methane ignitions can transition to more severe coal dust explosions, like in the Upper Big Branch (UBB) mine disaster in 2010 [1][2]. Explosion risks may exist in longwall operations if methane accumulates 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 [3][4]. Of particular concern is that the machine-mounted methane sensors did not prevent the UBB explosion even though investigators confirmed their functionality [1]. In addition, methane monitoring within the gob area is difficult as the caved area is inaccessible. Mine operators often employ methane drainage through gob ventilation boreholes (GVB) and nitrogen injection to prevent the formation of explosive gas zones (EGZs) in the face and gob areas. These methods are commonly used for progressively sealed gobs [5][6] but are less effective for bleeder-ventilation panels. To evaluate the flow pattern and gas mixtures in these critical areas, a 1/40th-scale physical model of a longwall coal mine panel was built [7][8]. To complement and guide the development and testing with 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 physical model. The physical experiments are used to validate the CFD model. The validated CFD model can help reduce the time and number of experiments required for different ventilation scenarios.

The combination of CFD and scaled physical modeling can be used to develop more reliable atmospheric monitoring practices and provide an improved understanding of the gas mixture formation inside the gob for different ventilation scenarios. The goal of this project is to develop early detection methods to improve methane explosion prevention and mitigation strategies in longwall coal operations.

2 Physical Model Overview

The 1/40th-scale physical model has dimensions of 7 m long by 6 m wide and 0.61 m high. The modeled active longwall panel includes the longwall face, gob area, the surrounding mine entries, and the ventilation control required to simulate

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different ventilation scenarios. The scale 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 entry dimensions are 145 mm wide and 72.4 mm high, 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 segments or carts (FC) consisting of 10 shields per cart. These face carts can be advanced individually to simulate different shearer cutting scenarios and gob lengths. Automation is integrated into the shearer using a Bluetooth connection to allow movement across the face, and adjustment to each shearer arm height and drum rotation depending on the simulated scenario [7][9].

Each gob cart is 0.6 m long, 0.5 m wide, and 0.61 m high. The model can accommodate 11 columns and up to 6 rows of gob carts. The gob carts can be filled with different materials to simulate different gob porosity and permeability distributions observed in the real longwall gob. Figure 1 shows a computer-aided design (CAD) image of the physical model, while Fig. 2 shows the actual assembled physical model.

Surrogate methane gas inflow into the model occurs through two main injection systems, allowing independent control of flow rates to the face and gob regions. Figure 2 shows the assembled physical model and the coal face injection system. Due to safety concerns, methane is substituted with a mix of 70%He/30%CO_2, which has a similar molecular weight as methane gas. In addition, CO_2 is used due to it being relatively easy to detect as a tracer gas within the model. The second injection system, shown in Fig. 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

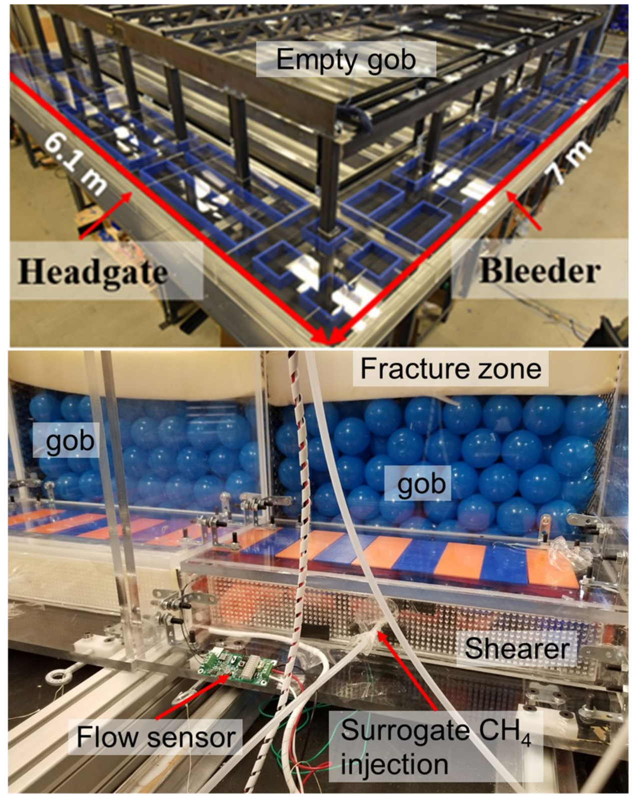


Fig. 2 Assembled physical scale model showing overview of the model without gob module (top) [10] and close-up view of the longwall face area with gob module inserted (bottom)

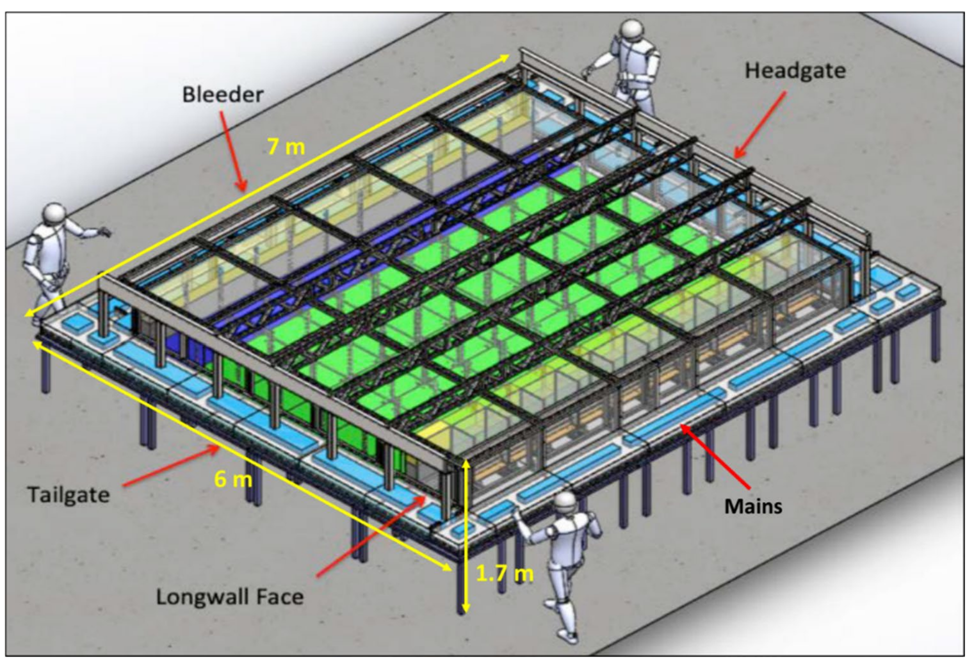


Fig. 1 CAD isometric view of the 1/40th scale physical longwall model [7]

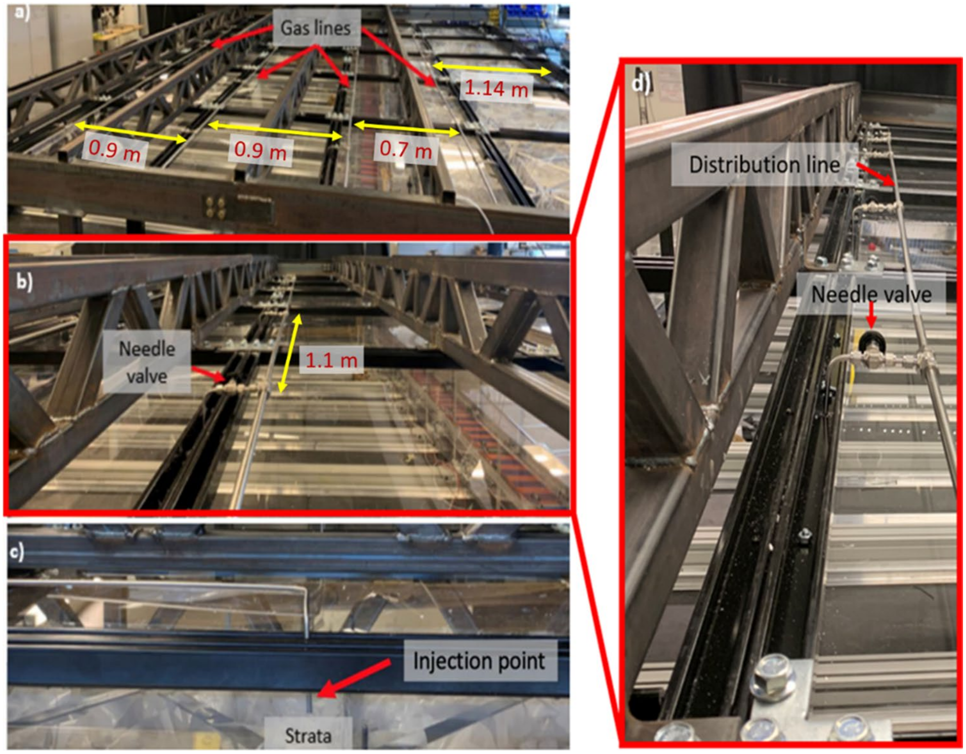


Fig. 3 Strata simulated methane gas injection system. **a** Overview of the gas system. **b**, **d** Close-up view of a single distribution line. **c** Close-up view of an injection point into the strata [10]

diameter, and each injection point to the gob contains a needle valve to adjust gas inflow.

Figure 4 shows the placement of the velocity and CO_2 sensors in the physical model. The diamonds and their respective colors represent the location of velocity and CO_2 sensors.

The face carts have a combination of plexiglass piece and permeable foam that acts as a gas manifold to distribute the injected gas, as shown in Fig. 5. These manifolds consist of 6 mm-diameter holes, spaced every 12 mm. Behind the manifold is a 25-mm-thick, porous foam used to simulate the uncut coal that also diffuses the incoming surrogate methane. Figure 6 shows the flow sensor installation inside the longwall face area.

Figure 7 shows velocity sensor installation to measure air velocity in the mine entries. To prevent obstruction in the entries, the flow sensor circuit board and cables are placed inside the hollow support pillars.

Two flow sensors and a CO_2 gas sensor are installed on six gob carts to analyze flow and CO_2 distribution inside the gob area. The location of these six instrumented gob carts is interchangeable with an uninstrumented gob cart to analyze different areas of the gob. Figure 8 shows the mesh enclosure to protect the flow sensors and CO_2 sensor installed inside the gob area.

3 CFD Model

ANSYS Fluent v. 18.2 is used for the CFD simulation. The CFD model is developed based on the 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:

- The longwall face consists of 11 face segments or carts, 110 shields, armored face conveyor, and a shearer, which have been represented reasonably similar compared to the physical model.
- Mine entries and ventilation controls, such as stoppings and regulators.
- Gob carts consist of front gob, back gob, and center gob segments with adjustable gob rows.
- The strata gas injection system has flow lines, nozzles, and valves.

Figure 9 shows an example of the model geometry separation for CFD meshing purposes. The arrows indicate the interface connections to facilitate assembly in the Fluent software.

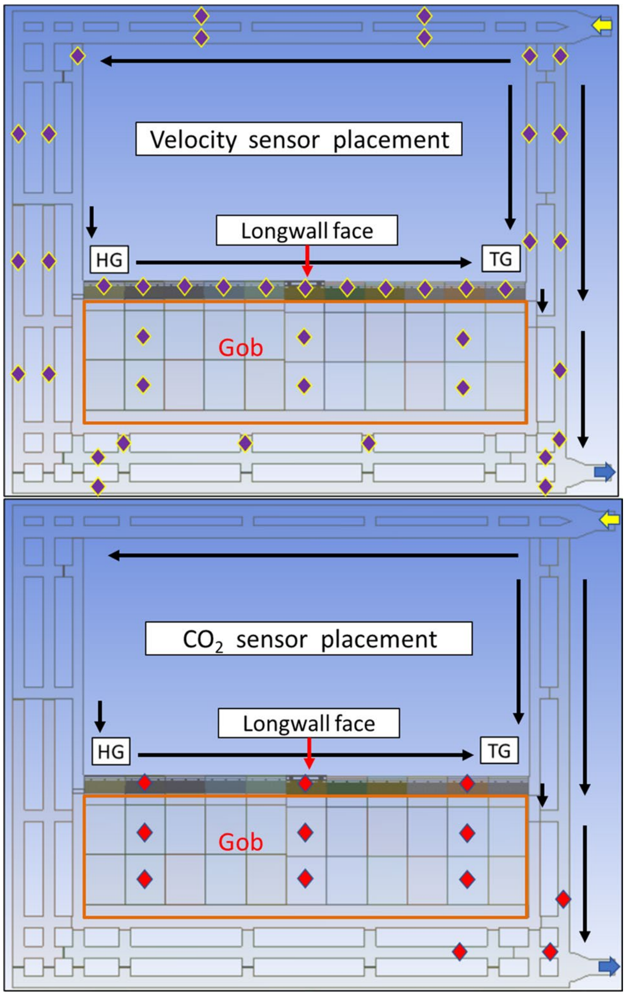


Fig. 4 Velocity sensors (top, purple diamonds) and CO_2 sensors (bottom, red diamonds) placement within the physical model for two rows gob insert setup

In the physical model, a porous foam is used to represent the uncut coal, as shown in Fig. 6. 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 the longwall face area that matches the actual flows delivered to the physical model. The gob and strata height can be adjusted within the available space inside the model, to a maximum height of 0.61 m. The strata injection system can also be adjusted to deliver the methane gas either to the top of individual strata layers or into the top of the gob. In the physical model, porous foam is used to represent the strata on top of the gob. In the CFD model, a porous zone with adjustable viscous resistance is used to model the strata.

Figure 10 shows a close-up view of the longwall face area and porous zone that represents the uncut coal, while Fig. 11 shows the strata injection system

Depending on the focus of the study, certain sections of the CFD model can be re-meshed to refine the area of interest. For example, to analyze flow patterns and gas distribution in the longwall face area, the longwall face mesh will be refined, and the strata injection system will be simplified to reduce computational time, and results validated against experimental data. 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 Fig. 12.

The following assumptions are currently used for the CFD model:

- The stoppings are modeled as a porous medium with base viscous resistance value of $1 \times 10^{13}/m^2$ used to represent well-constructed stoppings with minimal leakage. These stoppings can be changed to solid objects to represent gob seals in U-type ventilation patterns.
- The regulators are modeled as porous media with adjustable viscous resistance to reduce the computational effort of having to redraw the model each time to adjust the flow. The viscous resistance for each regulator is adjusted with the desired flow passing through the regulator in the physical model.
- The gob and strata zones are modeled as porous media with adjustable viscous resistance. For detailed studies in a specific area of the gob, partial discrete gob models can be substituted into the desired areas.

Table 2 shows the model settings used for the simulation.

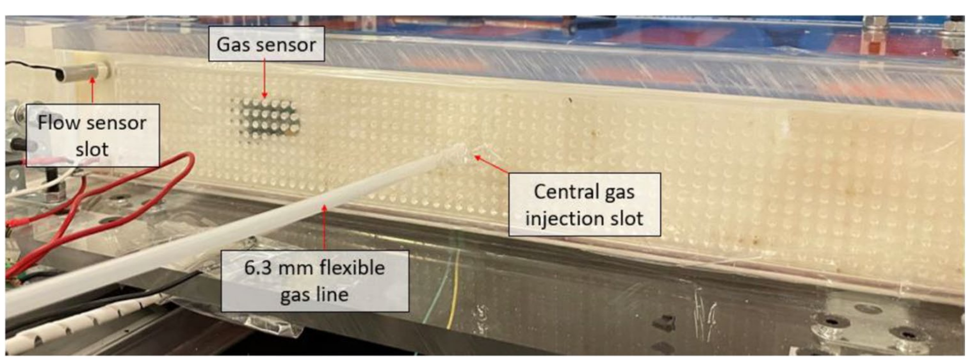


Fig. 5 Outside view of plexiglass manifold in a face cart

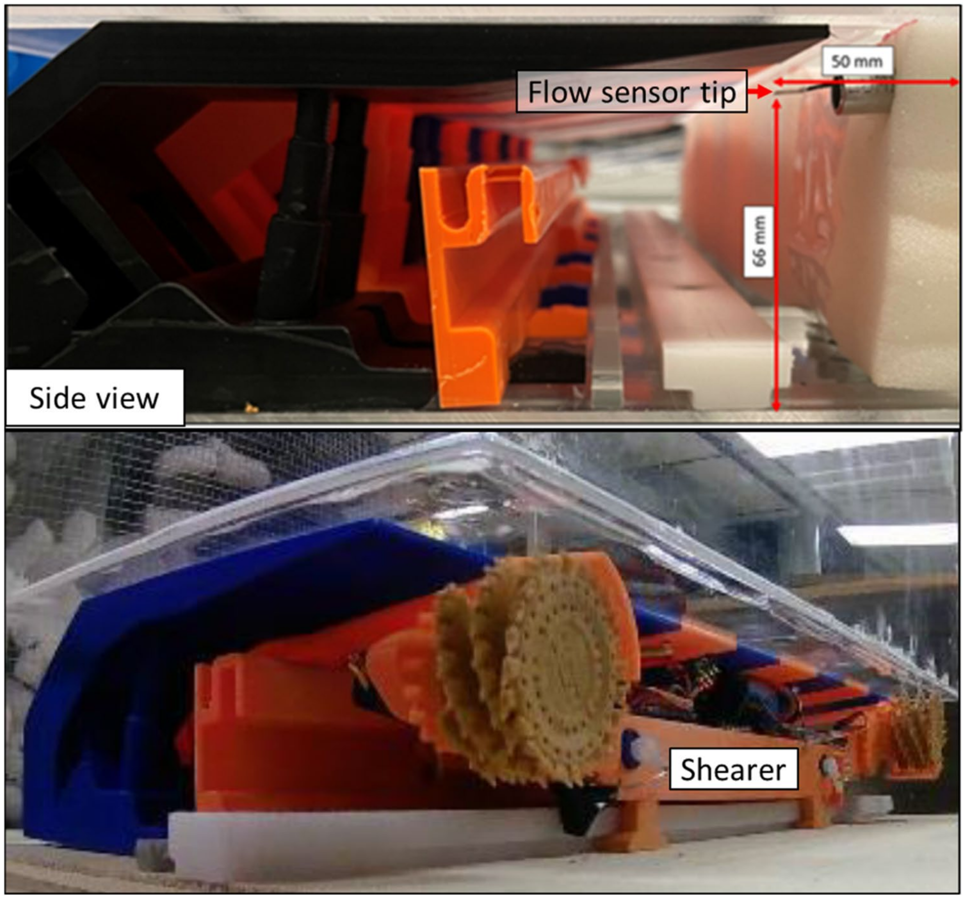


Fig. 6 Inside view of plexiglass manifold (top) and scaled shearer model (bottom)

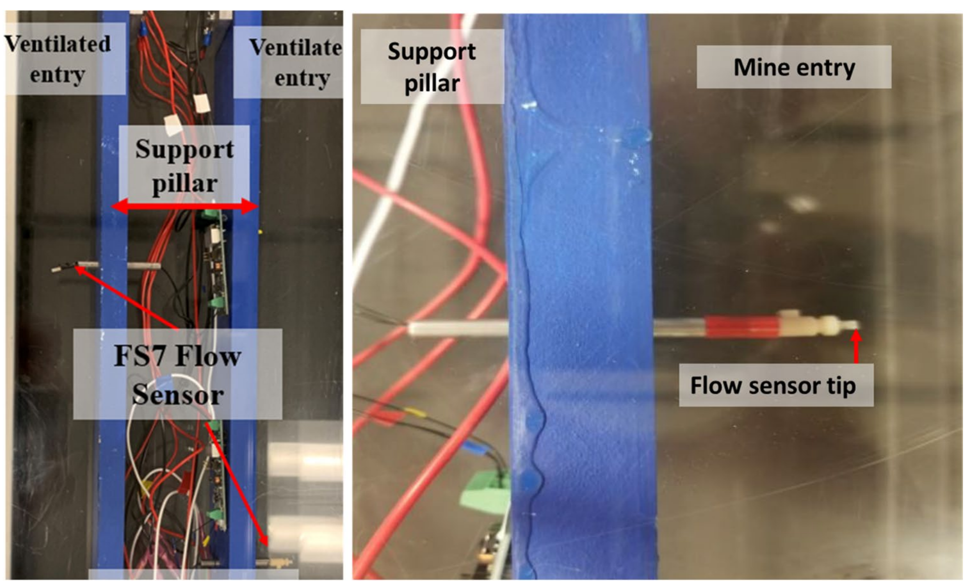


Fig. 7 Placement of mass flow sensors within pillars and sensor tip in the mine entry

4 CFD Simulation of Methane Distribution

For the model setup, mass flow inlet boundary conditions are used for the inlets at the main and strata injection points, while pressure outlet boundary conditions are used for the model outlet at the bleeder exhaust. The main inlet provides 110 L/s of fresh air. The amount of CH_4 surrogate gas supplied to the strata injection lines is set to 1.1 L/s, which is approximately 1% by volume of the

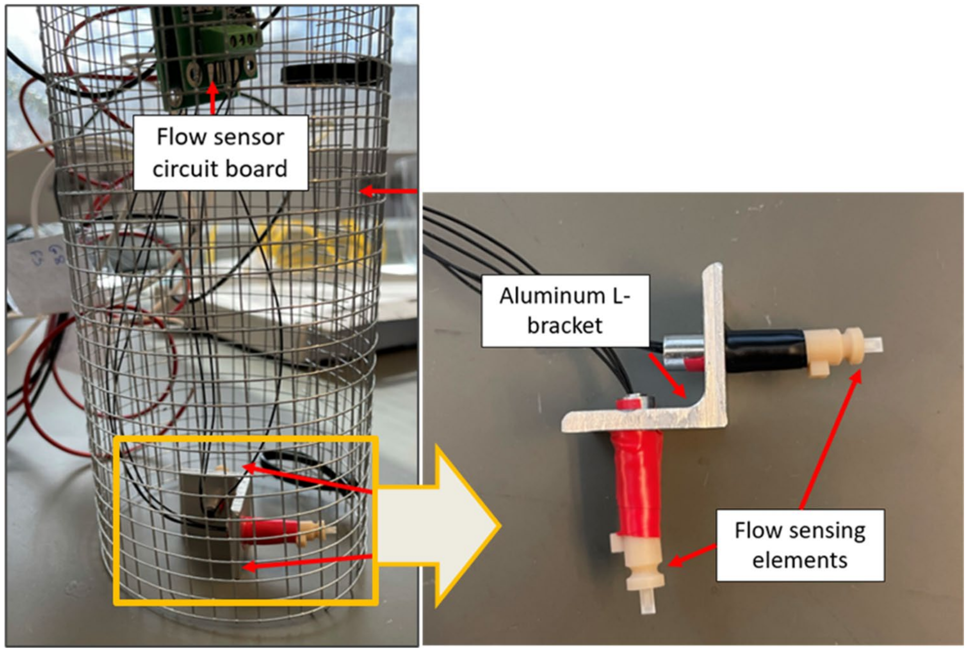


Fig. 8 Meshed enclosure used to protect the sensors (left) and array of bi-directional flow sensors (right) for flow measurement inside the gob

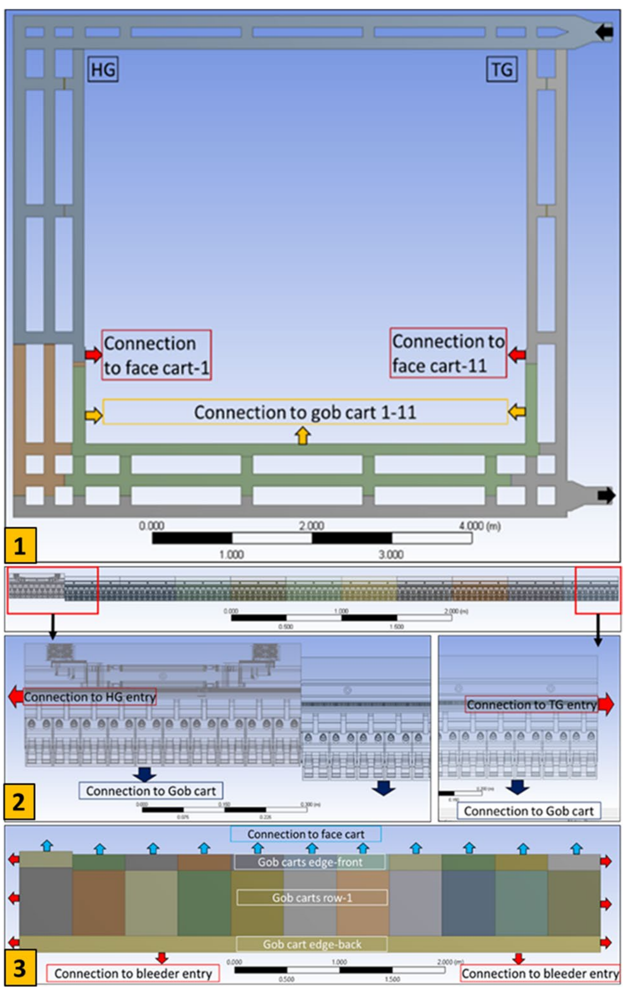


Fig. 9 Model geometry separation — mine entries (1), longwall face (2), and gob (3)

fresh air supplied from the main intake. An additional 1.1-L/s methane surrogate is supplied to the uncut coal face. The total methane surrogate inflow to the model is 2.2 L/s. The modeled gob height is 30.5 cm, while the strata is 7.6 cm high, equivalent to 12.2-m gob and 3-m coal height at full scale. Both the gob and strata are modeled as porous medium zones. For the gob resistance, the gob fringe resistance — 2 outside rows of gob modules — is assigned a viscous resistance value of $6.5 \times 10^6/m^2$, while a viscous resistance value of 1.05×10^7 $/m^2$ is assigned to the 5 rows of the center gob. These viscous resistance values are based on the physical test done with 58-mm- and 38-mm-diameter plastic spheres packed randomly in the gob. The coal strata on top of the gob is assigned a viscous resistance of $1 \times 10^8/m^2$ based on a test of the foam material used to represent strata in the physical model.

Figure 13 shows the simulated flow pattern inside the model for the bleeder ventilation system colored by airflow velocity, while Fig. 14 shows the methane distribution inside the model in the longwall face and in the gob and strata regions.

The results show that continuous leakage occurs across the longwall face as the airflow travels from the headgate to the tailgate. Parametric studies varying the flow rate from the main inlet and gob resistance show different leakage rates across the face ranging from 40 to 80% leakage. This leakage rate is within the expected leakage rate typically observed in real mines, which is around 50% [4] or up to 70% [11], depending on the gob's characteristics. In bleeder-ventilated gobs, some of the leaked air enters the bleeder entries through the crosscuts in the face on both sides of the gob, while the rest travel to the back of the

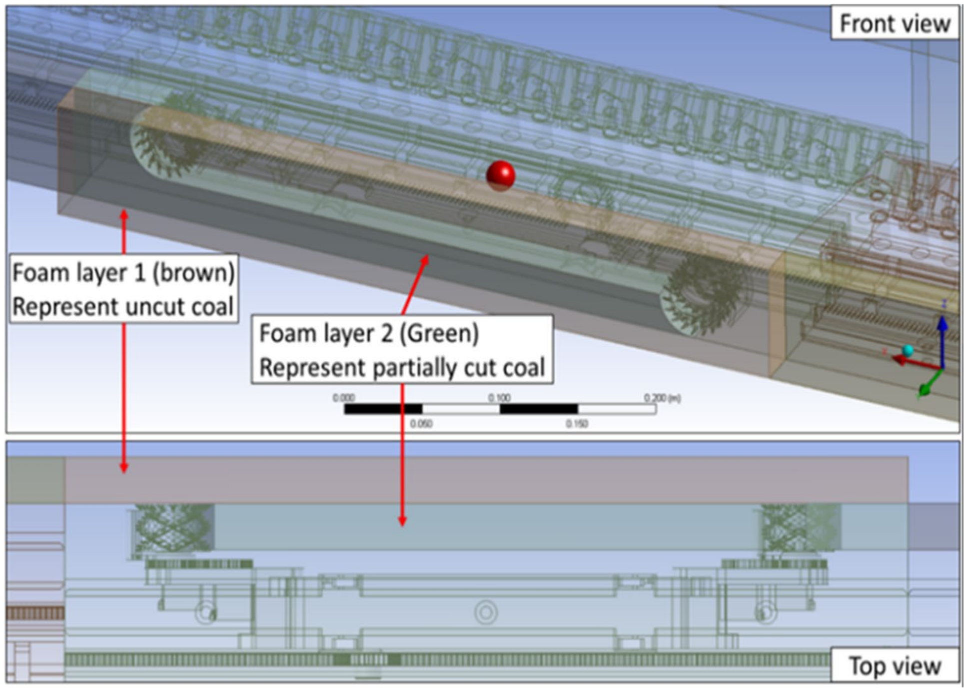


Fig. 10 Geometry longwall face with shearer and porous medium that represents uncut coal, shown from front view (top) and top view (bottom)

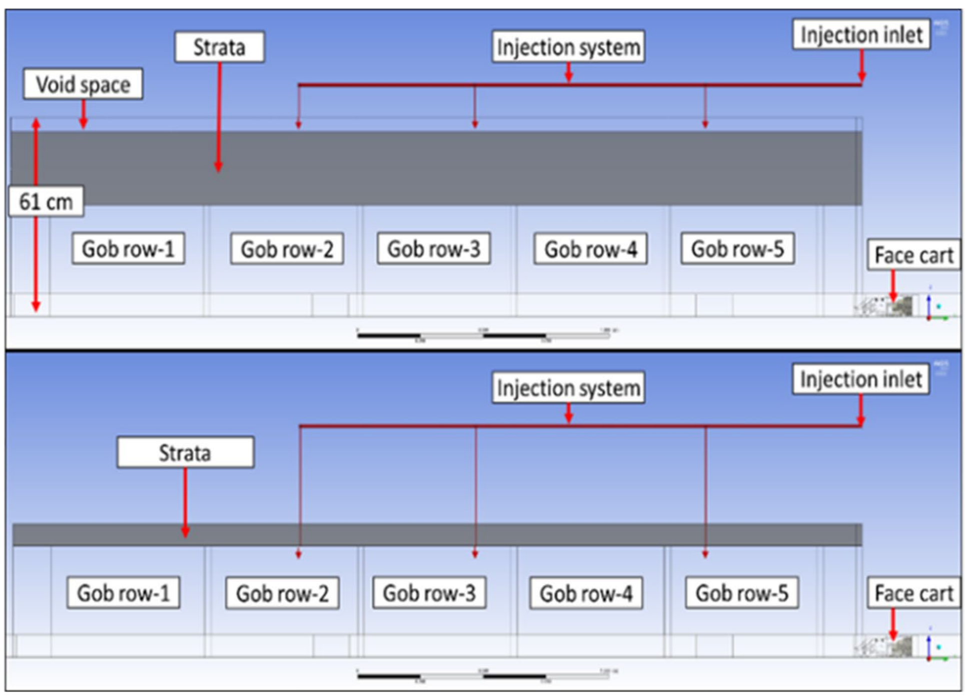


Fig. 11 Cross-section view of adjustable strata and the gas injection system

Table 1 Mesh summary

Segment	Mesh 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

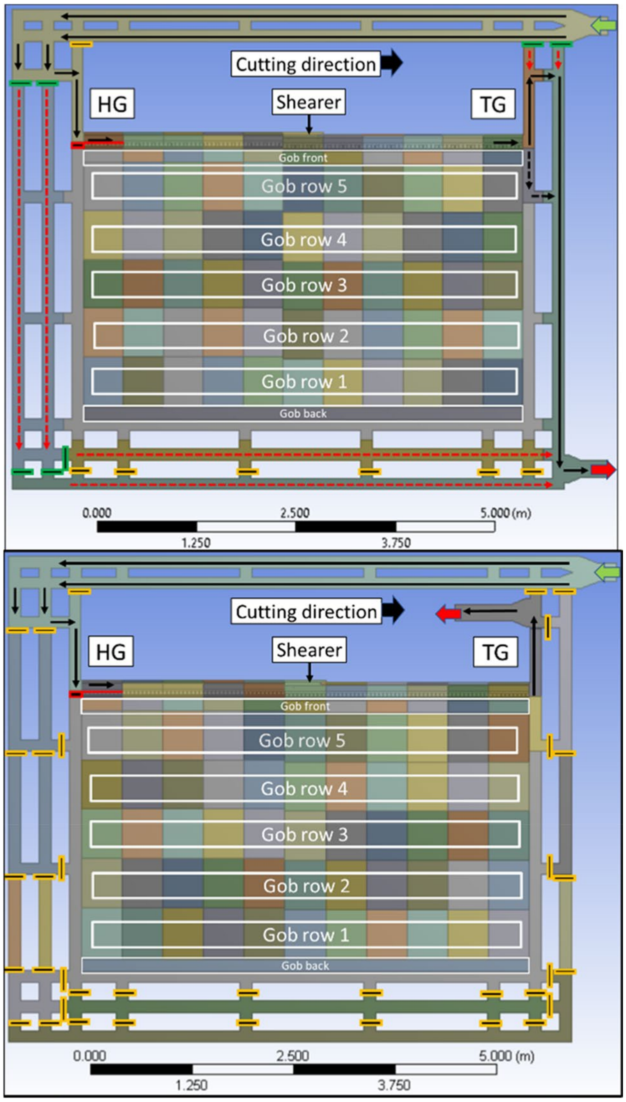


Fig. 12 Schematic of 5 rows of gob for a bleeder (top) and progressive sealed (bottom) ventilation system. The red line represents face curtain extending across the first face cart, while green- and yellow-colored rectangles represent regulators and stoppings, respectively

gob, matching common observations in the industry [12][13][14].

Figure 14 shows a high concentration of methane in the coal strata horizon and in the top region of the gob, where the methane is injected. Most of the methane in the lower gob area, especially on the headgate side, is diluted by the fresh air leaking from the longwall face. Some methane accumulations can be seen at the tailgate side of the gob.

5 CFD Simulations of Methane Surrogate and Comparisons to Experimental Results

Since methane is explosive, it was substituted with an inert gas mixture to analyze methane distribution and explosive concentrations inside the gob and longwall face. An important parameter is the fluid flow and mixing behavior of the surrogate gas compared to methane. A 70%He/30%CO_2 mixture was chosen as it has a similar molecular weight (16 g/mol) as methane. Methane equivalent concentrations are determined from CO_2 sensor readings. Methane and surrogate gas transport was investigated using the CFD model. Results in Figs. 15 and 16 demonstrate that the surrogate mix compares well to methane. In these cases, the shearer is located in the middle of the longwall face, in face cart 6. It should be noted that although the strata geometry was included in the model, 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 sensors are installed.

CFD simulations with the He-CO_2 surrogate show a similar gas distribution and flow behavior inside the longwall face area, especially where the shearer is located. In Fig. 15 right, the outlet carries 0.57% CO_2 by volume, which is equivalent to the 1.9% CH4 shown in Fig. 15 left.

An area of concern with high methane concentrations in the longwall face section is the tailgate corner, as methane continues to accumulate across the longwall face. With the shearer located in the center of the longwall face, Fig. 16

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	1×10^{-4} for continuity and momentum, 3×10^{-5} for turbulence, 1×10^{-5} for gas species, and 1×10^{-6} for energy
Boundary conditions	Mass flow inlet and pressure outlet
Porous zone	Gob, strata, and uncut coal face
Operating conditions	Pressure: 81 kPa (elevation of Golden, CO); temperature: 297 K

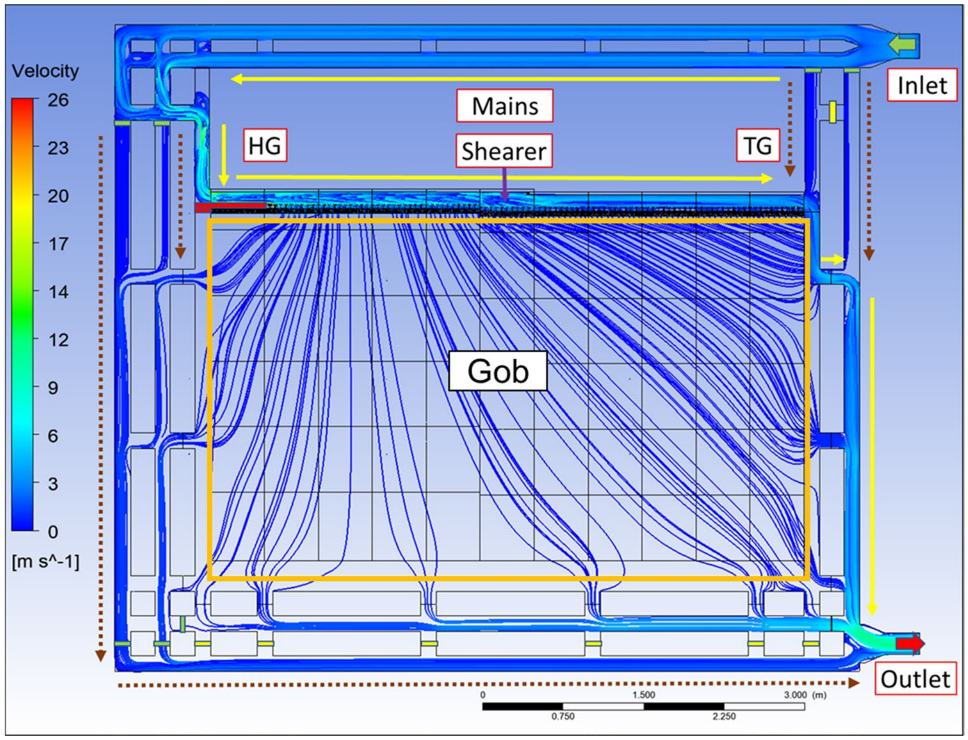


Fig. 13 Plain view of velocity streamlines showing flow distribution for a bleeder ventilation pattern, outlining the paths of fresh air supplied from the main inlet. The red line on the headgate (HG) side represents a face curtain extending across the first face cart, while the green- and yellow-colored rectangles represent regulators and stoppings, respectively

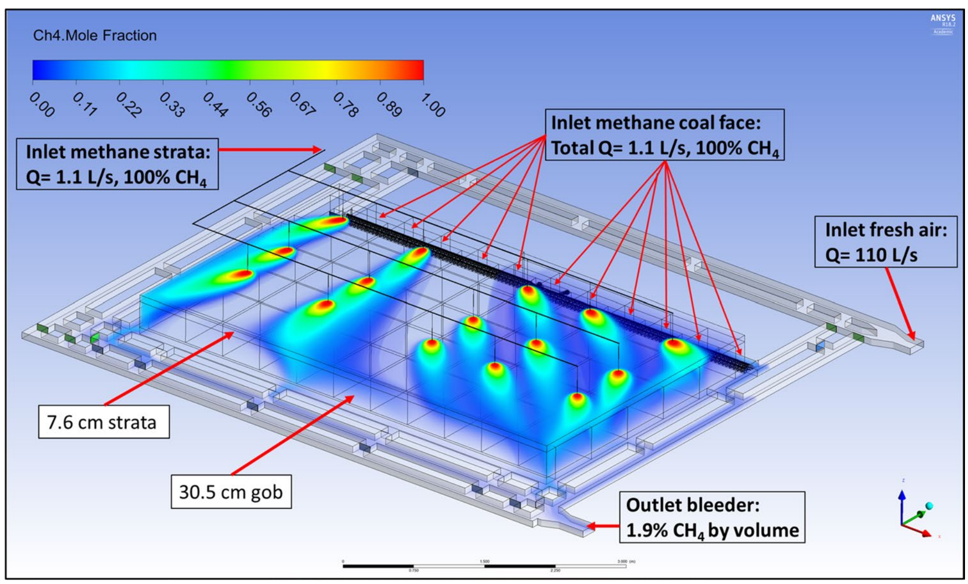


Fig. 14 Volume rendering of methane mole fraction. Methane injected from the top of strata

shows that explosive methane concentrations, marked in yellow to red colors, can form around the shearer tailgate drum. Modeling shows that the volume of this explosive gas zone (EGZ) increases as the shearer travel towards the tailgate. The methane concentrations inside the gob indicate that the leaked fresh air from the longwall face can sufficiently dilute the methane in the headgate area of the gob. A higher concentration of methane is observed around the top and edges of the gob, along within some crosscuts on the back corner of the gob.

The air flow patterns and methane distributions are verified in the scaled physical model. Airflow scaling in the physical model is important as it can significantly change the 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 the Reynolds number for the flow inside the face area. Details of the scaling approach and underlying calculations are described in [7] and [15]. CFD modeling results confirm the viability

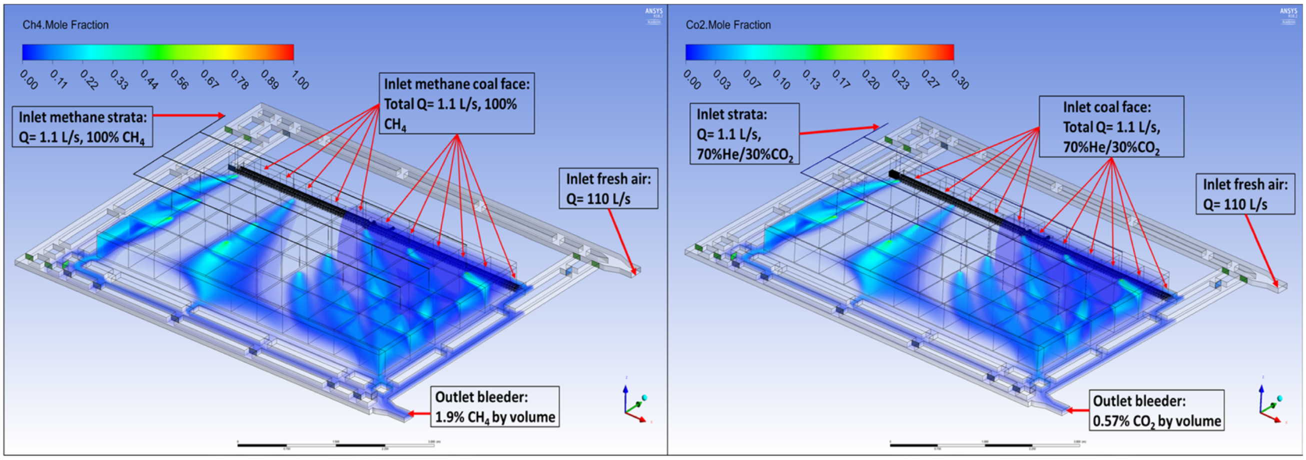


Fig. 15 Comparison of CH_4 (left) and CO_2 (right) distribution for 70% He/30% CO_2 simulated methane

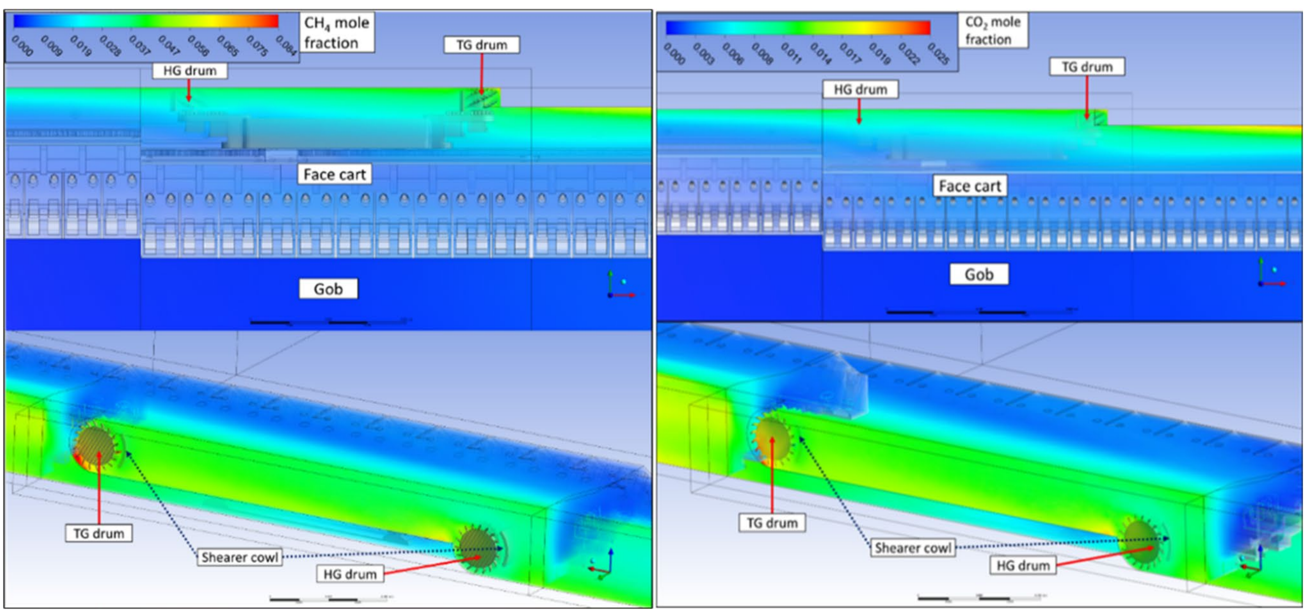


Fig. 16 Close-up view of longwall face area showing volume rendering of CH_4 (left) and CO_2 (right) distribution for 70% He/30% CO_2-simulated methane

of replacing the methane gas with a 70%He/30%CO_2 surrogate mixture [16].

The following section details the comparison of the CFD simulation results with the physical experiments for two rows and five rows of gob modules in bleeder ventilation scenarios.

5.1 Comparison Experiments Using Two Rows of Gob Modules

Figure 17 details the flow velocities with two rows of gob modules installed and the shearer located at face cart 11 (FC-11, last cart close to TG corner). This setup represents a bleeder ventilation system with a 30-cm (12 m)-high gob and a 7.6-cm (3 m)-thick coal bed. The measured velocities in the mine entries are converted into airflow quantity (L/s) for flow quantity balance verification. The front and back gob fringe areas, shown in tan color in Fig. 17, along with the partially collapsed gate entries surrounding the gob, shown in yellow color, are filled with 58-mm-diameter plastic balls. The center part of the gob, shown in light and dark green shades, is filled with 38-mm balls.

For the inlet flow conditions presented in Fig. 17, a total of 150 L/s of fresh air is supplied from the main inlet.

Fig. 17 Estimated flow quantities in the physical model for ~ 150 L/s supplied fresh air scenario. The shearer was located at the TG end of the LW face at face cart 11

A total of 3 L/s of the surrogate gas mixture is injected into the physical model, with 50% of the total flow (1.5 L/s) distributed to the longwall face, and 50% (1.5 L/s) injected into the gob. The gob injection lines from the strata are extended to directly inject 70%He/30%CO_2 into the gob carts at the middle gob elevation, 15.2 cm above the model floor, equivalent to 6 m above the bottom of coal. The experiment data represents 300 s of experiment, with every sensor in the model sampled at 1 Hz. Figure 18 shows three different probing depths, 30, 50, and 80 mm from the coal face, for the face airflow sensors that measure velocity at the longwall face. Figure 19 shows the flow velocities recorded for these sensors over the length of the face. These flow profiling tests show that the probing distance will impact the measurement, especially closer to the headgate side where flow reattachment occurs.

The results of the scaled physical experiments are compared with results from the CFD model. Two test scenarios that were compared are as follows:

1) Test 1 (T1): Main fan set at 150 L/s fresh air supplied to the main and 3.0 L/s methane surrogate injected into the model (1.5 L/s to longwall face, 1.5 L/s to the gob area).
2) Test 2 (T2): Main fan set at 100 L/s fresh air supplied to the main and 3.0 L/s methane surrogate injected into the model (1.5 L/s to longwall face, 1.5 L/s to the gob area).

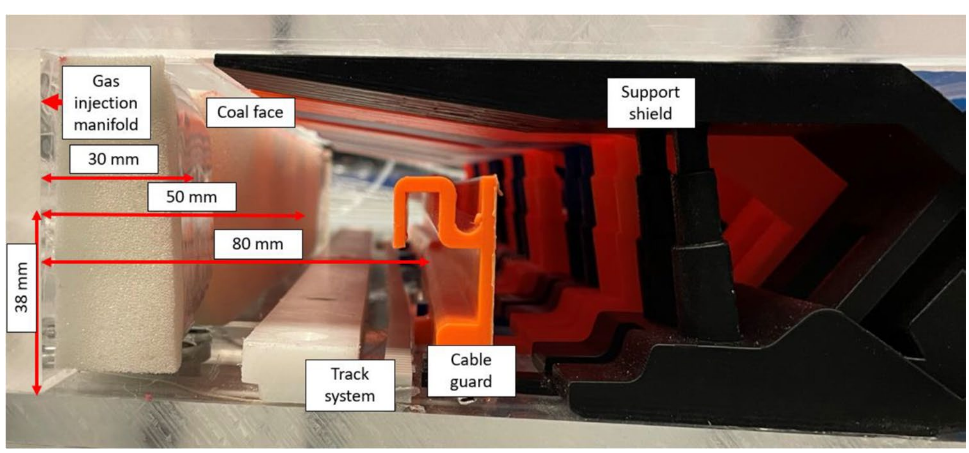


Fig. 18 Illustration of the probing depth and height for the data presented in Fig. 19 [10]

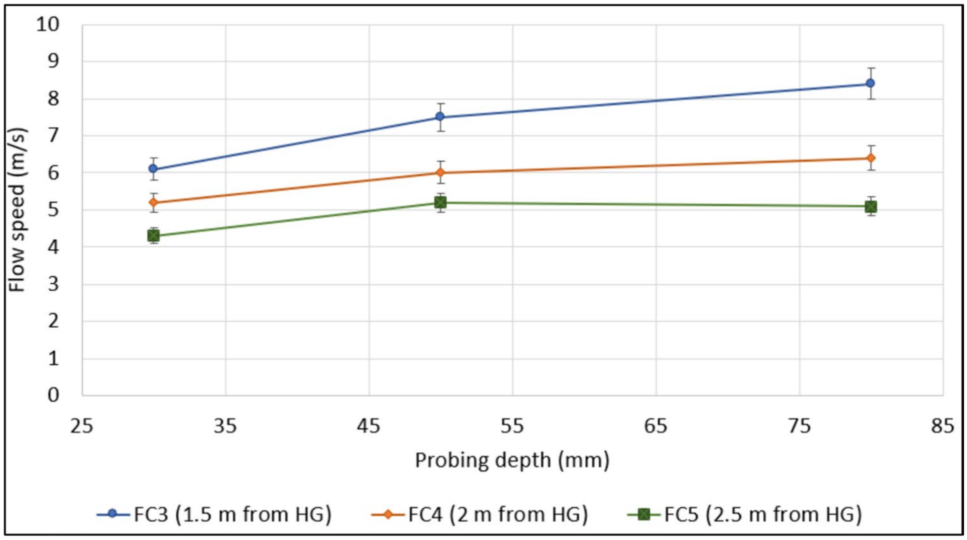


Fig. 19 Flow profiling across the longwall face at three face modules [10]

Figure 20 compares the experiment result to the CFD model. Note that in the experiment, the flow sensors are inserted at a probing depth of 24 mm from the simulated coal face, with the CFD results corresponding to 24 mm ± 6 mm probing distance to account for possible sensor placement deviation in the physical model. The shearer is located at face cart number 11, i.e., near the tailgate.

The results show that CFD and scaled physical models show overall good agreement in the velocity profile across the face in both tests. Velocities near the headgate side show greater discrepancies between the models due to the flow separation and reattachment as the airflow makes a right angle turn from the headgate into the face and creates turbulence.

Figure 21 shows the installation of CO_2 sensors used to determine the surrogate methane content in the physical model. The sensors are embedded into the permeable foam that represents the uncut coal face. This setup allows direct gas concentration measurement at the coal face with minimal flow obstruction by the sensor.

Figure 22 shows a comparison of the surrogate methane profile across the longwall face between experiment and CFD prediction. Note that the three CO_2 sensors are installed in face carts 2, 6, and 10, and the CFD data correspond to a 24-mm probing depth. The measured CO_2 concentration is converted into the equivalent methane concentration. The shearer is located at face cart number 11, near the tailgate.

The comparison shows again that the CFD models agree well with the experiments. The predicted methane concentration at face sensor locations 2 and 6 are within 0.5% CH_4 equivalent, while the predictions at location 10 agree within 1% CH_4. Both models also confirm that the methane concentration in the face increases towards the tailgate side.

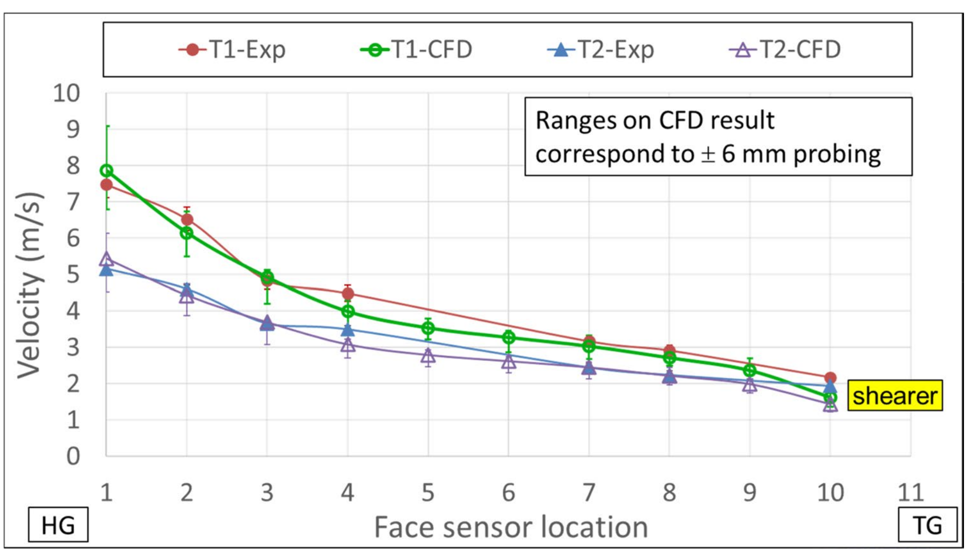


Fig. 20 Comparison of flow velocity profile across the longwall face between experiment and CFD prediction

Figure 23 shows the methane-equivalent readings in the longwall face and the flow profiles in the gob for 150 L/s of fresh air flow to the main and 3.0 L/s methane surrogate injected into the model. This experiment reveals the formation of two explosive gas zones, about 5% at the tailgate and about 8% in the gob near the bleeder fan exhaust. Figure 24 shows that both EGZs are also predicted by the green shading in the CFD models.

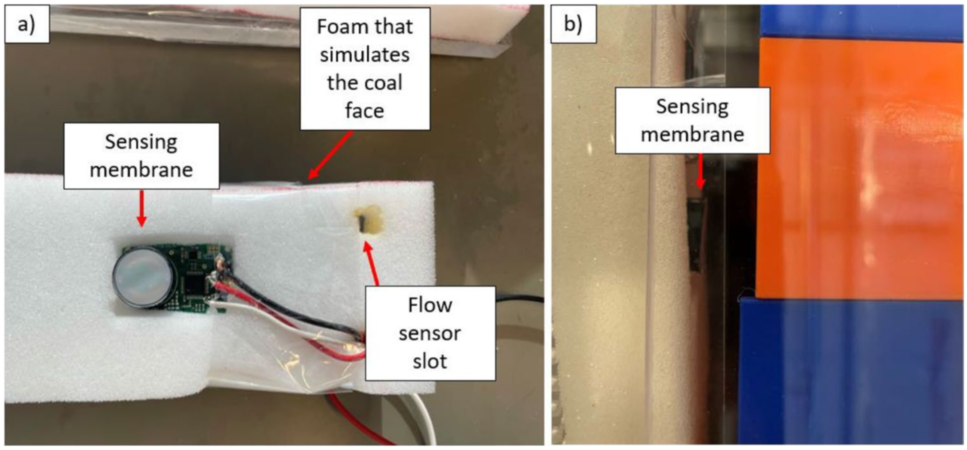


Fig. 21 **a** CO_2 sensor installed into the longwall face. **b** Top view of a face module showing how the sensors are placed into the foam [10]

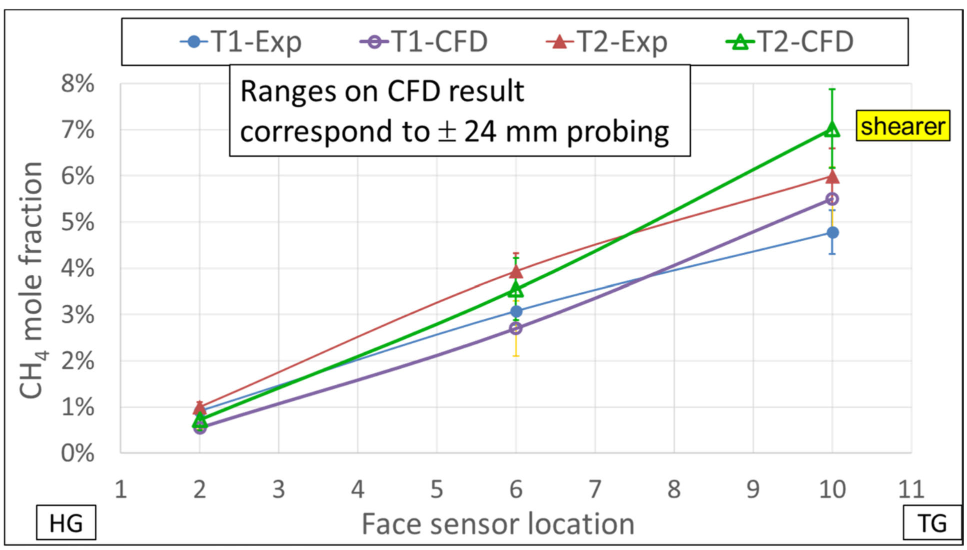


Fig. 22 Comparison of methane equivalent across the longwall face between experiment and CFD prediction

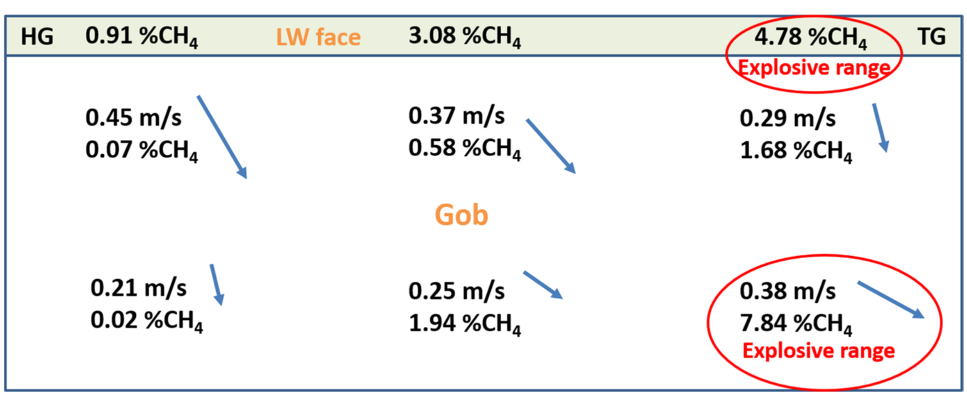


Fig. 23 Methane equivalent gas readings in the gob and longwall face and flow profile in the gob, for test 1

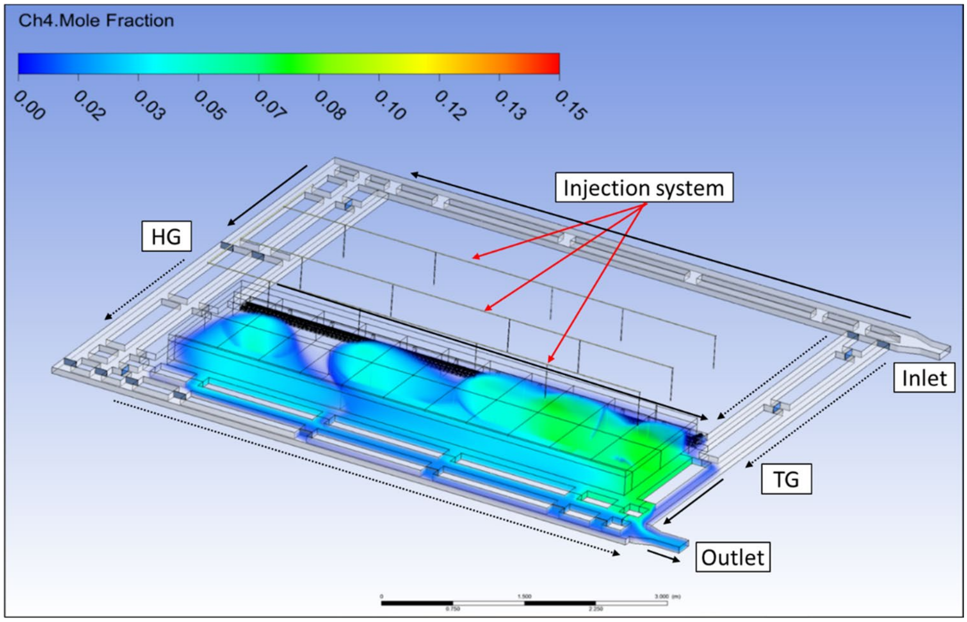


Fig. 24 CFD model simulating the methane concentration in the physical model for the bleeder ventilation with 2 rows of gob scenario, for test 1

A CFD analysis was performed to determine the sensitivity of the CO_2 sensor placement inside the gob. Two methods were used to analyze the trend. The first method varies the sensor locations within a sphere of 50-mm radius from the sensor locations in the physical model. Minimum, maximum, and volume average concentrations are calculated within each sphere. The second method varies the CO_2 sensor locations along vertical lines ranging across the height of the gob. Figure 25 shows the locations of the 50-mm-radius spheres and the vertical lines.

Figure 26 compares the equivalent methane concentrations inside the gob between the experiment and CFD models for 150 L/s airflow into the main and 3.0 L/s methane surrogate injected into the model. The naming convention GC R1-2 represents gob cart row 1 column 2, while GC R2-2 represents gob cart row 2 column 2, and so on. The 5-cm-radius coverage was chosen to account for the error bars associated with the placement of the sensors within the gob.

The minimum and maximum methane concentration values within the 5-cm-sphere radius-predicted CFD models indicate sharp gradients in concentration at locations GC R2-2 and GC R2-10 (see Fig. 27). In location GC R2-2 (shown in purple lines in Fig. 27), the CFD model predicted close to 0% methane concentration at the lower part of the gob, which then increases to around 1.5% at the center gob elevation. In location GC R2-10 (shown in light blue lines in Fig. 27), the CFD model predicts a steep increase of methane concentration from around 0.6% at the lower half of the gob, to 4.8% at the upper half of the gob. The other four sensor locations do not show a significant change in methane concentration in the vertical direction based on the CFD model.

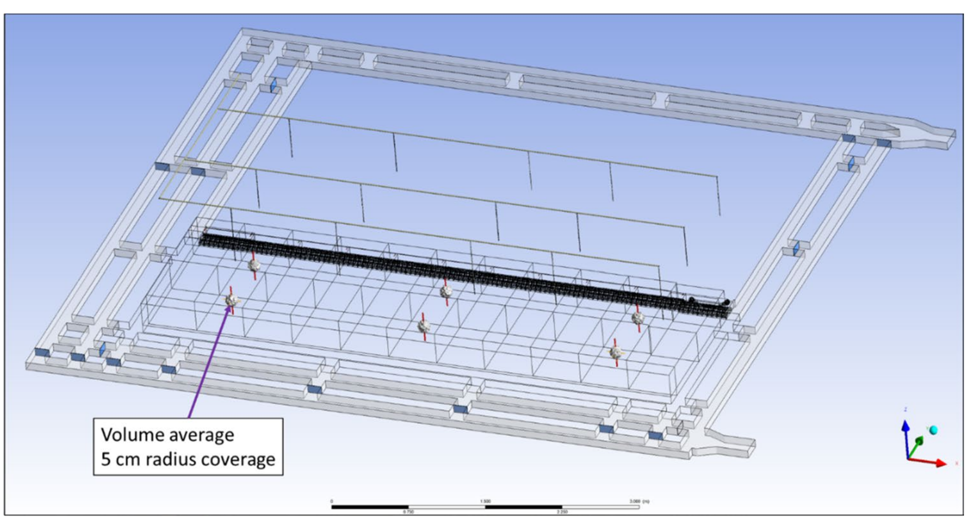
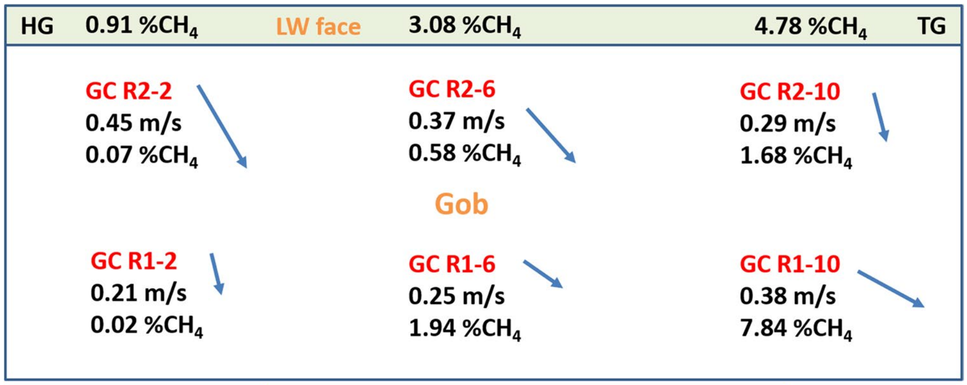


Fig. 25 Gob sensor placement sensitivity study using the CFD model



	5 cm radius coverage			
Location	CH_4 min	CH_4 max	CH_4 average	Experiment
GC R1-2	3.57%	3.77%	3.68%	0.02%
GC R1-6	3.46%	3.60%	3.50%	1.94%
GC R1-10	6.53%	6.69%	6.63%	7.84%
GC R2-2	0.02%	3.29%	1.14%	0.07%
GC R2-6	0.18%	0.20%	0.18%	0.58%
GC R2-10	0.70%	5.34%	2.83%	1.68%

Fig. 26 Comparison of methane concentration inside the gob between the experiment and CFD model, for test 1

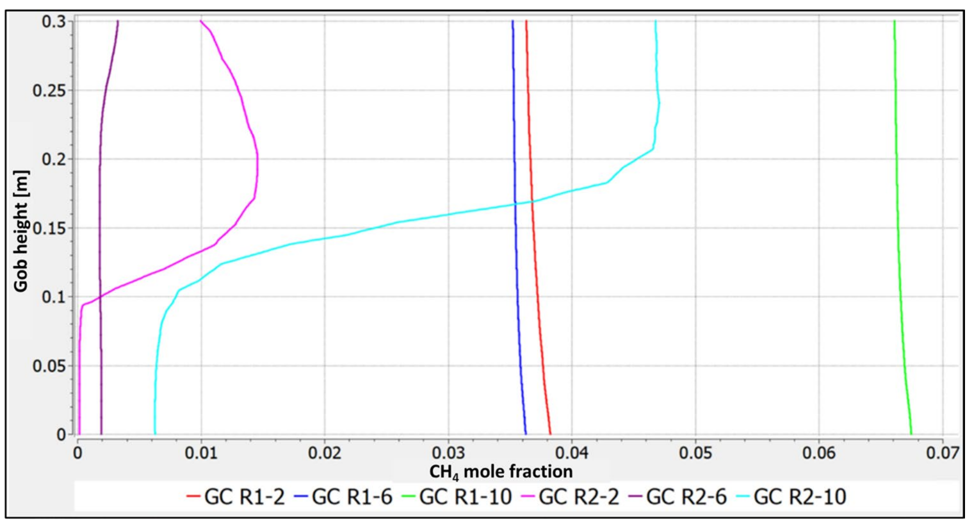


Fig. 27 CFD model prediction of methane concentration gradient inside gob using vertical lines, for test 1

In the other locations, the CFD models provide reasonable agreement with the physical model. There is a notable discrepancy in the methane concentration for location GC R1-2 that will be investigated further.

5.2 Experiments with the Longwall Face Advanced to Five Rows of Gob Modules

Similar flow and gas experiments were conducted with 5 rows of gob module inserted. Figure 28 shows a schematic of the physical model with airflow rates in liters per second shown in the mine entries, and flow velocities and equivalent methane concentrations in the gob. In this experiment, approximately 100 L/s of fresh air was supplied from the main fan inlet. A total of 0.4 L/s of surrogate gas was injected to the longwall face, while 1.6 L/s was injected into the gob at center elevation, ~ 15 cm (6 m) above the model floor. The red arrows in Fig. 28 indicate the direction of the air flow in the mains, gate entries, and bleeders. Figure 29 shows the corresponding CFD model with methane distribution and gas sensor locations. The CO_2 sensors are also installed in the middle height of the gob.

The equivalent methane concentration readings inside the gob suggest higher accumulations on the tailgate side (GC R3-10, GC R1-6, and GC R1-10 in Fig. 28), which is to be expected in a bleeder system where the bleeder fan is pulling

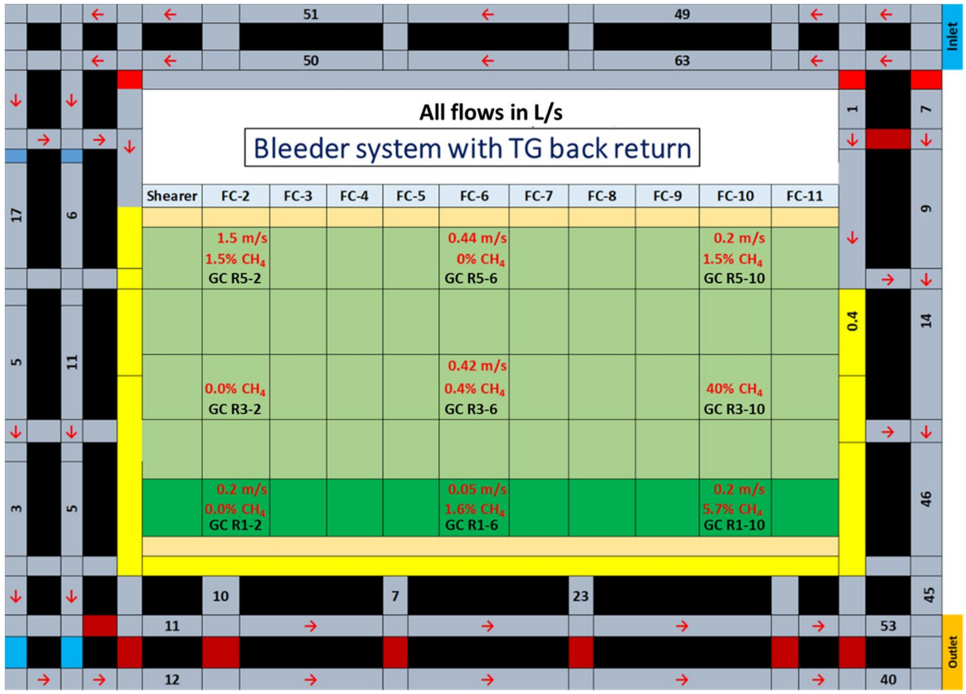


Fig. 28 Experiment result for bleeder with 5 rows gob, shearer at face cart 1. One hundred liters per second of fresh air supplied from the main inlet, 0.4 L/s of surrogate gas injected to the longwall face, and 1.6 L/s injected into the gob

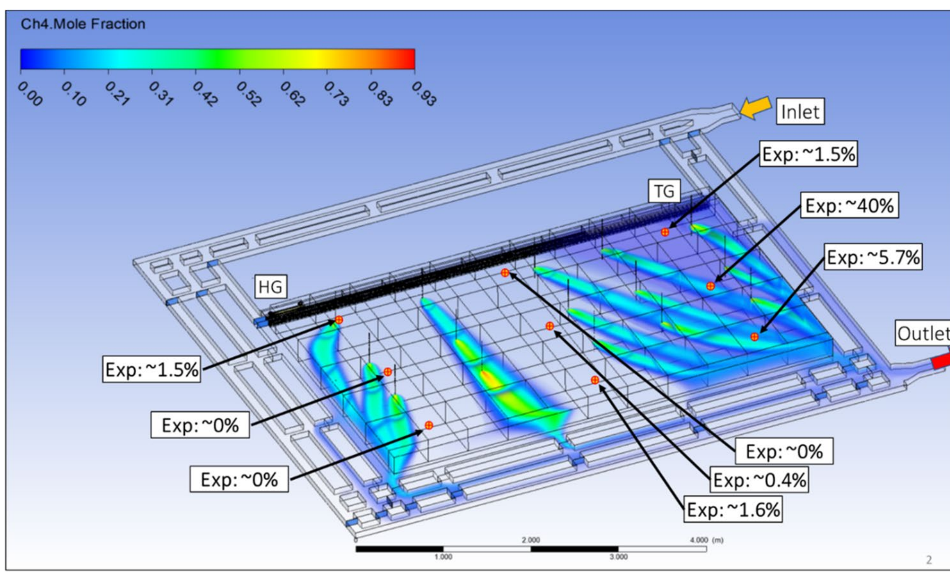


Fig. 29 CFD model with 5 rows of gob and a bleeder system, showing methane distribution and sensor locations inside the gob. The annotated methane equivalent concentrations represent measurements in the scaled physical model

the flow towards the back of the panel. The CFD model helps visualize the methane distribution inside the gob for this particular injection setup. The CFD models also predict that most of the injected surrogate methane gas flow towards the back tailgate side of the gob. The three gas injection locations, GC R5-2, GC R3-2, and GC R1-2, Fig. 28, show that some of the gob flow enters the bleeder entry at the headgate side and return to the gob near the back of the panel. The CFD-computed flow pattern explains the high methane reading at GC R5-2, as the sensor at this location is close to the injection point, and near 0% methane readings at GC R3-2 and GC R1-2, as these sensors are located on the tailgate side of the injection locations. Sensors GC R5-6 and GC R3-6 also measured close to 0% methane, which agrees with the CFD prediction that shows that the methane plumes do not pass these sensor locations. The sensor at GC R3-10 measured the highest concentration, most likely because the sensor located directly in the plume of the nearby injection point. There is a discrepancy in the sensor GC R1-6 result that requires further investigation.

Figure 30 shows a close-up view of the CFD simulation in the longwall face. The coloring indicates equivalent methane mole fraction iso-surfaces. The shearer is located at headgate side.

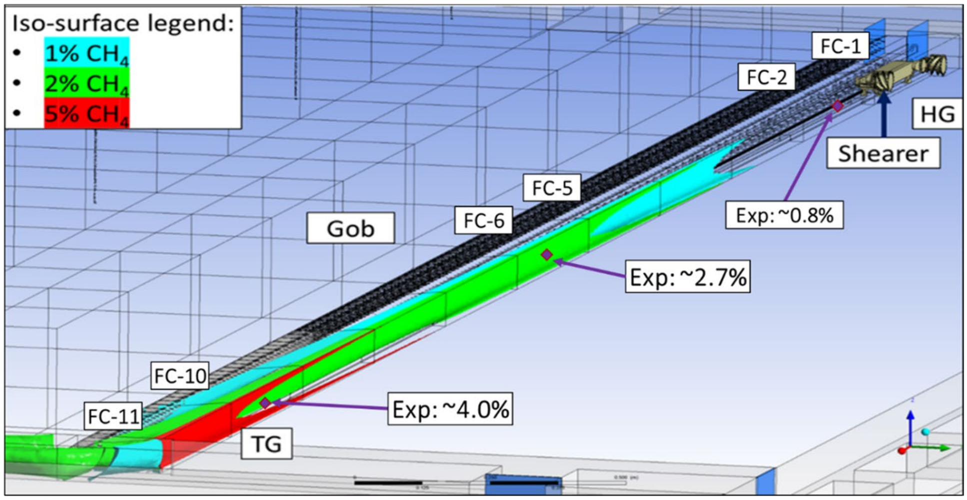


Fig. 30 CFD model of the 5-row bleeder system showing prediction of methane distribution across the longwall face. The annotated methane equivalent concentrations are from measurement (converted from CO_2) in the physical model

The CFD results agree well with the experimental results. The predicted methane at the first measurement at face cart 2 near the headgate is less than 1% CH_4, as shown by the lack of blue-colored iso-surface in this area. The second measurement location at face cart 6 predicted methane concentrations between 2 and 5%, closer to the 2% based on the observed green-colored iso-surface that started to form at face cart-4. This is in line with the measurement results done in the physical model, which is around 2.5–3% depending on the shearer location. The CFD simulation for the third measurement location at face cart 10 near the tailgate predicted methane concentrations between 2 and 5%, closer to the 5% based on the red-colored iso-surface that begins to form in face cart 10. This methane prediction agrees with the measurement in the physical model that shows around 4% methane. Overall, the CFD and physical models agree well in their prediction of the methane distribution across the face.

6 Conclusions and Future Work

CFD models are used to aid in the design and development of a 1/40th-scale physical model of a longwall coal mine. CFD simulation results compare well to physical sensor data measuring airflow and surrogate methane concentrations.

Data from the scaled physical model, resulting airflow patterns, leakage rate, and methane distribution, are used to validate the CFD models. Comparisons of experiment and CFD simulation results also show overall good agreement in terms of flow patterns and gas distribution in the longwall face and gob regions. This confirms the viability and advantages of this coupled modeling approach, which can be used to develop more robust, full-scale longwall coal mine CFD models to aid in the design and improvement of ventilation and air quality monitoring practices to reduce the risk of longwall mine explosions.

For future work, the CFD model will be used to simulate different ignition scenarios, such as face ignitions by the shearer cutting drum [3] or in-gob ignitions behind the longwall shields. Different gob modeling methods, such as partial or full discrete gob modeling [12], can be incorporated into the CFD model for more accurate gob representation in the physical model and allow in-gob ignition simulation.

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Declarations

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Conflict of Interest The authors declare no competing interests.

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