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REVIEW

Computational Fluid Dynamics Analysis of Full-Scale Methane Explosions Compared to Field Testing Results

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Abstract
There is a long and unfortunate history of accidental explosions in underground coal mines in the United States. While safety controls have reduced the potential for methane explosions in the US, there still exists the potential for methane explosions if safe mining conditions are not maintained or an unforeseen accident occurs. Multiple analyses have been completed with various models being developed to help understand the potential impact of methane explosions. This paper establishes a methodology and presents initial results as part of ongoing research and testing to develop and validate a computational fluid dynamics (CFD) model to predict the potential pressures resulting from underground methane explosions. Full-scale field-testing results are compared to current full-scale CFD models to predict, analyze, and test the pressures resulting from underground methane explosions. Results indicate that, although there is some correlation between the established CFD model and field-test results, further improvement and verification of the CFD model remain warranted.

Keywords Computational fluid dynamics · Modeling · Methane explosion · Explosion pressure

1 Introduction

Methane explosions have historically been a contributing cause to mine disasters in coal mines throughout history. A mine disaster is classified by the Mine Safety and Health Administration (MSHA) as a mine accident claiming five or more lives [14]. The percentage of mine disasters in the United States classified as an accident involving an explosion is 71% for the time period between 1970 and the present, and 80% since 2000 and the present, as reported by MSHA [14, 15]. Included in these mine disasters are the Sago Mine explosion in 2006 and the Upper Big Branch (UBB) Mine explosion in 2010. Both incidents were a result of underground explosions in a coal mine and resulted in 12 and 29 fatalities, respectively [15].

While the percentage of mine disasters resulting from explosions is high, there has been a significant decrease in the loss of life associated with each accident in the United States since 1970. This can most likely be attributed to increased mining regulation, specifically including the Federal Coal Mine Health and Safety Act passed in 1969, methane control methods, and improved safety standards [16]. However, there have still been numerous accidents and fatalities involving methane explosions over the years that

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are not considered mine disasters. The most recent accidents resulting in loss of life were in 2016 and 2019 [15]. The first incident involved one fatality and occurred on July 29, 2016. It involved a miner sustaining serious injuries while completing welding work by standing on grating over a mine shaft when a single methane gas explosion was ignited within the shaft [15]. The second incident involved one fatality and occurred on July 31, 2019. It involved multiple methane gas explosions being ignited while work was being completed to seal an intake shaft that resulted in a miner being subjected to explosive pressures [15]. These accidents speak to the need for continual improvement in safety controls and standards around methane explosions.

Explosions in underground coal mines are typically caused by the accumulation of flammable gas and/or dust in the air being exposed to an ignition source [3]. There are two major types of explosions resulting from methane explosion incidents. The first is the initial explosion. The initial explosion poses a high initial risk to the miners in the direct vicinity of the explosion and a low initial risk to miners not in the area of the explosion. The second is the potential for secondary explosions. Secondary explosions pose a risk to miners trying to escape the mine, take refuge, rescue trapped miners, or rehabilitate the mine. Both types of explosions can contribute to increasing the chance of subsequent explosions by causing damage to ventilation, ground controls, or equipment and by kicking up coal dust that may help propagate any secondary explosions [30].

It is important to know how methane explosions affect areas underground to help make decisions to improve the safety of the miners by preventing, suppressing, and mitigating explosions [3]. Actions to enhance miner safety can include identifying the optimal construction and locations for stoppings, seals, refuge areas, equipment, and other mine infrastructure. Sapko et al., [24] state that seals, rock dusting, and ventilation are the dominant controls in mitigating underground coal mine explosions. Stoppings are installed to separate different sections of an underground mine to assist with ventilation or isolate an abandoned area of the mine. They should be well constructed and keyed into solid rock, typically between pillars. Stoppings should also maintain quality seals to prevent unwanted mixing of the air from either side of the stopping [27]. The dynamic response of stoppings to potential underground explosions is specifically important in ensuring the safety of underground miners in the event that an ignition source is introduced to a flammable methane-air mixture. Previous research has studied the dynamic response of various types of stoppings using models of explosion overpressure curves to evaluate the effects of material type, reinforcement, thickness, and other constraints of blast resistance [10]. Field experiments need to be conducted to determine the air overpressure curves from underground methane explosions to effectively model the response of the environment to the explosion incident. Some methods for better understanding how methane explosions affect these areas include instrumenting full-scale field tests, developing simulation models, and building scale tests to simulate alternative scenarios.

This paper presents a model of the potential impact of a methane explosion in underground coal mine environments based on analyses of previously conducted research. Pressures from the explosion are analyzed to understand how they travel through and interact with the environment in an effort to improve understanding of what pressures are potentially exerted on personnel, ventilation controls, and equipment based on their location in the underground mine. Existing research on full-scale testing is used as a baseline for comparison and determining the validity of generated models [20, 21]. A developed computational fluid dynamics (CFD) model is compared to full-scale testing results and is proposed to be used to develop an approach for generating a CFD model for methane explosion testing in physically small-scale mine network models to assist with understanding the impact of pressures generated by methane-air explosions.

2 Background

2.1 Previous Testing

The National Institute for Occupational Safety and Health (NIOSH) and MSHA have been investigating the impact of underground explosions as a response to the significant potential impact of such explosions on underground mining environments. A considerable amount of NIOSH's and MSHA's full-scale research and testing on underground explosions has occurred at the Lake Lynn Experimental Mine (LLEM). A total of 527 explosive tests were conducted from August 1983 to July 2008 [29].

The LLEM consisted of four parallel drifts extending off a previously excavated underground limestone mine. These drifts were connected by perpendicular drifts to simulate the layout of modern coal mines in the United States [3]. Three drifts (Drifts A, B, and C) were near each other and connected to the fourth drift (Drift D) via an extended perpendicular drift (Drift E) with bulkheads at both ends connecting to the primary drifts (Drifts C and D). The layout of the LLEM is shown in Fig. 1. Data collection stations for monitoring dynamic pressure, temperature, heat, and video have been installed and used in the five primary drifts over the course of testing [3]. The cross-sectional view of the methane and/or coal dust ignition zone in Drift D is shown in Fig. 2 [3]. Similar setups were utilized in monitoring

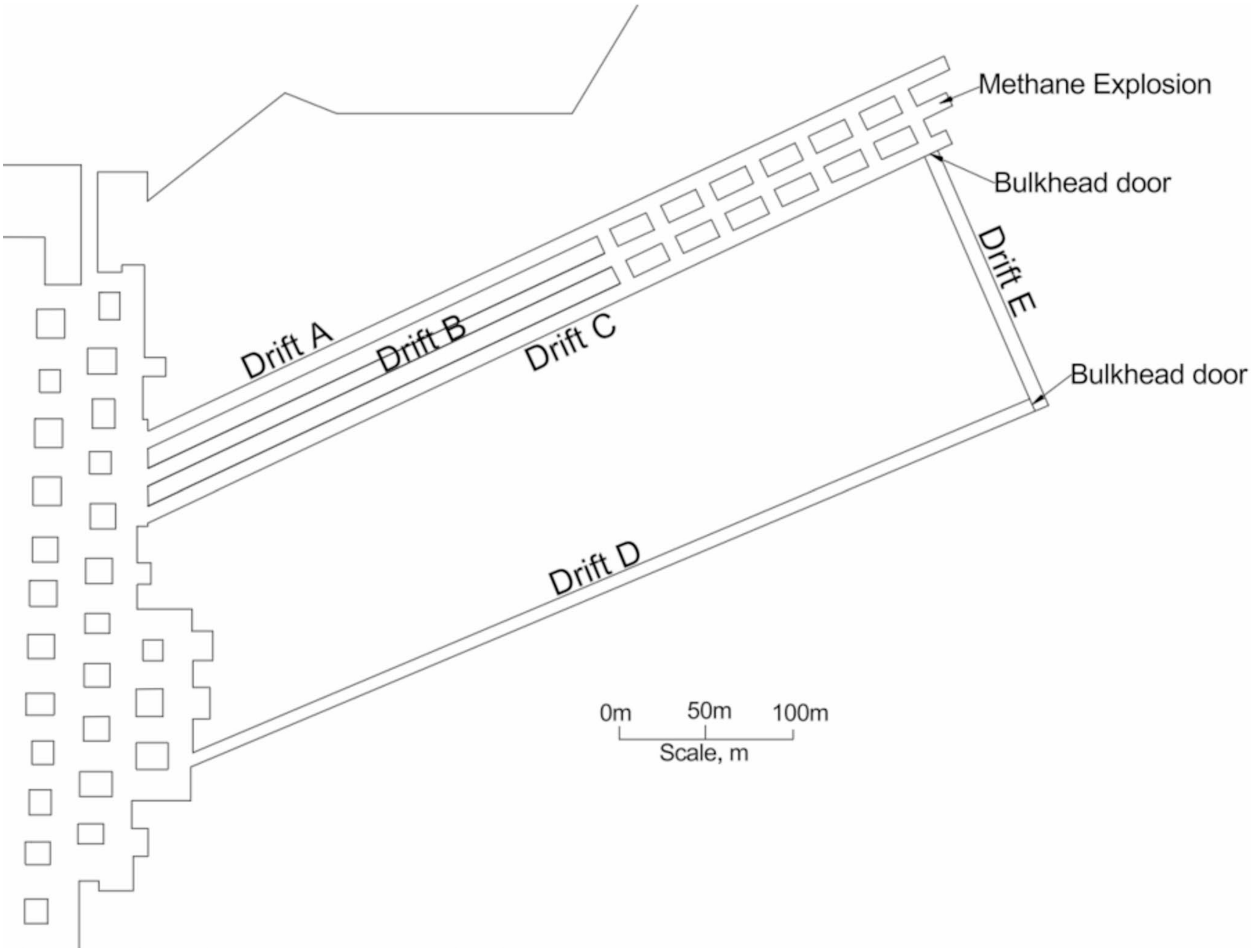

Fig. 1 Plan view of the Lake Lynn experimental mine (LLEM) (based on [3])

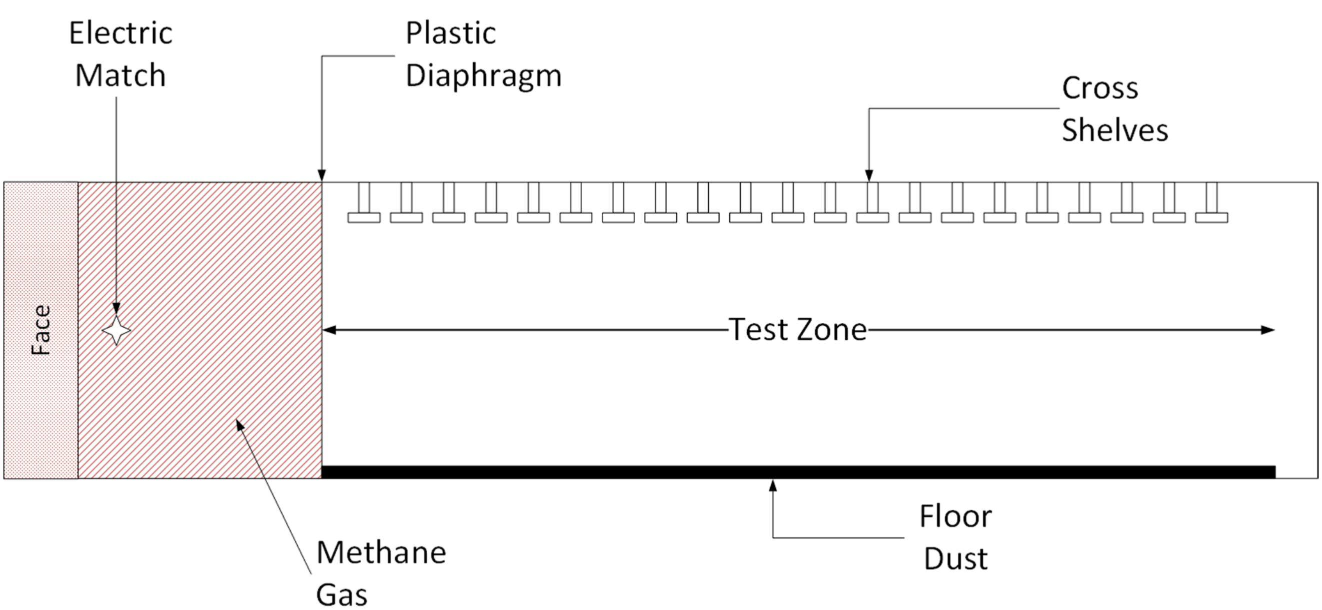

Fig. 2 Cross-sectional view of D Drift in LLEM showing gas ignition zone (not to scale) [3]

testing in Drift B, with additional monitoring in Drifts A and C.

A variety of test blasts were conducted at the LLEM site over the years. These tests investigated the impacts of many variations of explosive mixtures to characterize blast events by replicating many different explosion conditions. Testing has focused on methane percentage by volume, explosive gas volume, coal dust volume, and the ignition point. LLEM Test 471 consisted of igniting a 10% methane and coal dust mixture with coal and rock dust placed on the floor down the drift from the explosion source. Areas with pre-explosion dust mixtures of 67% and 80% incombustible material, with the remaining percentage coal dust, showed post-explosion levels of noncombustible material to be approximately 80% of dust mixtures [3]. Previous experimental mine tests demonstrated that explosions will not propagate through a coal dust and rock dust mixture with 80% or more rock dust [19, 25].

The modeling research presented in this paper focuses on methane-only explosions and does not consider coal dust explosions due to current rock dusting controls and safety precautions being implemented in most modern mines to eliminate coal dust explosions [5]. Many LLEM explosion tests using various test configurations were completed using the ignition of methane without coal dust. Test 347 measured the peak pressure at various distances from ignition, reviewing the impact of variable volumes in the drift resulting from bulkheads installed in crosscuts [5]. This test demonstrated that the volume change caused by the crosscuts did impact the peak pressures. Tests 468, 469, and 470 all reviewed the peak pressures with no crosscuts. Each test consisted of igniting different volumes of explosive mixtures of methane. These tests demonstrated that there was little reduction in peak pressure over distance in smooth-wall tunnels [5]. The distances of the data collection stations from the face of Drift D are shown in Table 1 for LLEM Test 469 based on data provided by NIOSH [21]. Test 469 also consisted of a methane-air mixture of approximately 10% methane [21]. LLEM Tests 484 and 485 evaluated the effect of unbarricaded crosscuts and various volumes of explosive mixtures of methane on the peak pressure over distances and at various locations within the LLEM test drifts. The results from Tests 484 and 485 were determined to correspond well with the results from Test 347 [5]. LLEM Test 485 was significant in characterizing the behavior of blast air overpressure waves in an underground coal mine with multiple headings and cross sections. LLEM Test 485 consisted of a methane-air mixture of approximately 10% methane being ignited in an 18.3 m (60 ft) long section of Drift B with a single point of initiation one ft off the floor near the face. Data was collected along Drifts A, B, and C at multiple data collection stations [20]. The distances of the data collection stations from the face of the drifts are shown in Table 2 for LLEM Test 485 based on data provided by NIOSH [20].

Additional research by Smith and Sapko [26] studied the detonation wave propagation behavior in single and multiple entry headings. This research demonstrated that peak air overpressures generated from unconfined explosives are influenced by the number of intersections in the heading. Smith and Sapko, [26] also demonstrated that the tunnel distance, cross-sectional area, number of intersections, and weight of explosives are helpful in predicting the behavior of low-pressure waves inside the underground workings. Their findings help identify the appropriate ventilation controls, protect miners, and assist with accident investigations [26].

Computing peak pressures in an underground mine network resulting from an underground explosion is critical for identifying the impact on personnel and equipment. A crew's proximity to an explosion determines their likelihood of survival, taking refuge, or complete escape [30]. Refuge alternatives need to be designed in a manner to resist certain air overpressures from explosions if miners survive an initial explosion and need to take refuge [30]. The United States Title 30 Code of Federal Regulations Part 7 specifically states that refuge alternatives should be designed to withstand 103.4 kPa (15 psi) of overpressure for 0.2 s [17].

2.2 Modeling Methods

One of the objectives for field testing and instrumenting underground explosions is to better understand how methane explosions impact underground mining environments. Performing field testing involves significant investments of time and resources, as well as exposing miners and researchers to risks associated with the testing environment. Alternative methods, such as modeling, can be used to investigate the impact of explosions on underground environments. Developing a full-scale field test can be time-intensive and costly. Computer models can become an effective and efficient tool for analyzing potential impacts of explosions as an alternative to more cost-prohibitive full-scale field testing [11]. Once a model is established, it can then be analyzed and tested against empirical site data to verify the accuracy of the model. An accurate model should produce results representative of field conditions and data.

Table 1 LLEM test #469 data collection stations (Drifts D) (based on [21])

DG-Panel		D-1	D-2	D-3	D-4	D-5	D-6	D-7	D-8	D-9	D-10
Distance from the Heading Face	ft	31	50	100	152	201	300	390	501	601	750
	m	9.4	15	30	46	61	91	119	153	183	229

Table 2 LLEM test #485 data collection stations (Drifts A, B, and C shown from top to bottom, respectively) (based on [20])

DG-Panel		A-1	A-2_81	A-2	A-3	A-4	A-5	A-6	A-7	A-8	A-9	A-10
Distance from the Heading Face	ft	22	81	132	183	233	283	355	453	550	649	807
	m	7	25	40	56	71	86	108	138	168	198	246
		B-1	B-2	B-3	B-4	B-5	B-6	B-7	B-8	B-9	B-10	
Distance from the Heading Face	ft	10	108	158	211	257	329	427	526	626	782	
	m	3	33	48	64	78	100	130	160	191	238	
		C-Face	C-1	C-2	C-3	C-4	C-5	C-6	C-7	C-8	C-9	C-10
Distance from the Heading Face	ft	0	13	84	134	184	234	304	403	501	598	757
	m	0	4	26	41	56	71	93	123	153	182	231

Models can produce a wide range of results depending on the input data, calculations, assumptions, and other processes and information implemented during the development of the model. It is important to verify that a model is accurate and representative of field conditions and data. Models should be verified against multiple tests to ensure they can repeatably predict the results of field testing accurately. Such results provide higher confidence in using modeling methods to determine the impact of underground explosions and help improve the safety of miners.

Modeling methods currently used in mining and other industries specifically include CFD modeling. CFD is a numerical modeling technique that applies mathematics, computer science, physics, and chemistry to simulate and understand fluid movement, the interaction of fluids, and fluid dynamics [2, 23]. Petrov, [23] states that confidence in CFD modeling must be established through a process of testing, adaptation, and validation.

CFD modeling has been applied in mining for various purposes. Some of the earliest applications of CFD modeling include studying face ventilation [12, 13]. Wala et al., [28] determined that CFD modeling was a useful tool for predicting the impact of changing ductwork configurations while studying the main ventilation of a mine's primary airways. CFD simulation results were verified with field data as a part of this study. Wala et al., [28] completed additional research to verify CFD modeling for small-scale and full-scale testing for the flow of methane using experimental results. The clearance of hazardous blast fumes from a muck pile in underground headings has also been modeled using CFD. Adhikari et al., [1] predicted dilution times and generated equations for predicting the time until threshold limit values of fumes were achieved and conditions were safe for miners to reenter the working area. Similar work in the clearing of hazardous blast fumes from a muck pile from block caving has also been completed [31]. CFD modeling methods have also been used for mine fire simulation and evacuation response [22].

In addition to their use in ventilation, CFD models have been used in modeling methane-air explosions. Explosions along the cutter head on a longwall were investigated by Juganda et al., [8]. This research demonstrated the viability of implementing a methane combustion CFD model. However, only the initial 200 milliseconds (ms) of the explosion propagation near the cutter head were reviewed. Looking at further propagation beyond 200 ms is required to understand more about the transition from initial combustion to detonation [8]. Cheng et al., [4] used numerical modeling to study how air overpressures at various intersections in underground mine networks were impacted by changes in the layout of the network. Through this research it was identified that the orientation of the intersections were impacted based on the intersection being a corner of bifurcated.

Additional testing has been conducted on explosive gas mixtures in gob sections of underground longwall coal mines. A bleeder ventilated gob system including two adjacent panels, one active and one mined, was modeled using CFD [6]. The model consisted of explosive mixtures in the gob that might compromise the effectiveness of the bleeder ventilation system. CFD model results were verified against previous models and studies and identified the potential for miners to be exposed to explosive mixtures under certain ventilation conditions [6]. Additionally, a 1/40th small-scale longwall was constructed and used to investigate various mine ventilation strategies for methane control and mitigating the potential for accidental explosions [9].

Industry can learn more about what potential issues to look out for and help prevent future accidents by conducting post-incident investigations. Some post-incident investigations have used CFD modeling to help better understand and identify the root cause of incidents involving methane explosions [26]. One specific example of a post-incident investigation utilizing CFD modeling is with the Sago mine explosion from 2006. These models were based on digital maps of the mine at the time of the explosion and considered the worst-case scenario for the incident. Established models, based on LLEM testing, were used to determine the mine seal and environmental response to the methane explosions. Several scenarios were simulated and validated based on good comparisons between pressures from calculated and measured pressure time histories from LLEM testing [11].

CFD modeling has also been used to evaluate blast pressures on the surface as well. Hansen et al., [7] modeled blast waves and pressures from gas explosion within surface structures using CFD models generated from LLEM field test data. A comparison between CFD analysis and code validation versus scaled distance for surface blasting was completed by Aramayo et al., [2]. Aramayo et al., [2] determined that the CFD simulation has benefits, specifically adapting the model to a wide range of scenarios, but ultimately identified scaled distances as having better correlation with empirical data.

Other industries have also used CFD models to predict air overpressures resulting from explosions. One example includes modeling for onshore petrochemical facilities. Hansen et al., [7] used a simplified CFD modeling approach to simulate and evaluate blast waves in response to direction, geometry, and processes of the facilities, gas cloud variations, and ignition location. CFD modeling results were validated using the area-to-volume scale and were relatively close to experimental data. Results also showed how directional effects and interaction with the geometry of the facility can influence the dynamics of the blast waves [7]. Additional examples include the United States Department of Defense using CFD models to study the blast effects of weapons [11] and [18] utilizing CFD to model open air blasts of the explosive trinitrotoluene (commonly known as TNT).

Verified CFD models can be highly beneficial, providing accurate predictions and have proven to be a verifiable method for modeling and predicting mine ventilation and impacts from explosions, specifically air overpressure. However, the computational time and confidence in a CFD model can still be a challenge in developing efficient and accurate models. Juganda et al., [9]. Confidence in CFD modeling can be obtained through the process of testing, adapting, and validating model results with empirical data from field testing [23].

3 Methods

3.1 CFD Modeling

The primary objective of this research is to develop a methodology for assessing air overpressures resulting from methane-air explosions in an underground coal mine. Currently, there is no way to know the exact impulse of such an explosion in an underground mining environment. Engineered estimates and assumptions need to be used based on experience and experimental results. The volume and concentration of a methane cloud are explicitly correlated to the pressures generated from an explosion [19]. Nagy, [19] found that a concentration of 9.5% methane produces the highest pressures. Various other site conditions, such as temperature, atmospheric pressure, and released pressure, can also be considered through modeling.

Various modeling methods are available for predicting peak pressure values in an underground mining environment. CFD modeling was selected for the numerical simulation of methane-air explosions. A satisfactory validation must be achieved through the implementation of CFD models through a process of design, testing, adaptation, and validation for a method to be proven viable for further research and field applications [23]. The steps taken for generating the CFD models is shown in Fig. 3 and include (1) generating a model of the shortened full-scale mine network, (2) setting up initial conditions and boundary conditions, (3) generating a computation mesh for the model, and (4) running the CFD model, simulating the release of pressure from the methane-air explosion.

Two primary methods for setting the initial conditions of the CFD models considered include the bursting balloon method and the initial impulse method. The bursting balloon method simplifies the effects of the explosion by

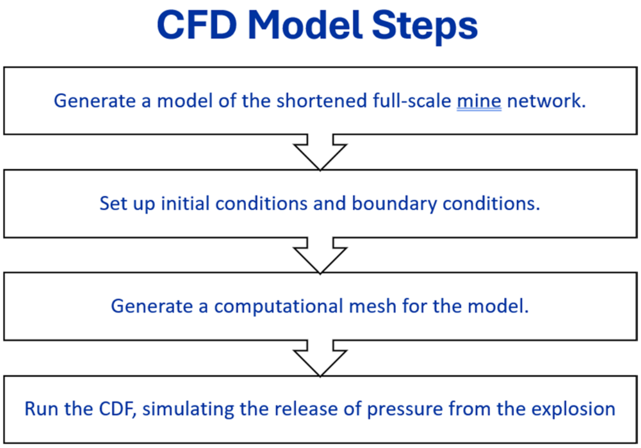

Fig. 3 CFD model steps

representing the pressures produced by the explosion with a high-pressure bubble, or balloon, of a known volume and geometry. When the balloon bursts, the high-pressure gases in the bubble are released, simulating the effects of an explosion on the surrounding environment [18]. The initial impulse method requires knowledge of the ignition surface's geometry and the total pressure impulse associated with the explosion. While the initial impulse method provides the most accurate predictions, the initial impulse is generally difficult to calculate or is unknown. The initial impulse can also vary from one site to the next based on variable and unknown field conditions. On the other hand, the bursting balloon method uses a much more practical and achievable data set. For this reason, the bursting balloon method was selected as the primary method used in the CFD models.

The setup of the CFD model included using total pressure boundary conditions. The boundary of the walls were set up to not include calculations for friction due to the rapid movement of the blast shockwave. No-slip wall conditions were used and roughness of the walls was not considered. A prism layer was implemented in the boundary layers to help account for the high velocities of the shock wave from the explosion.

The number of elements used for the computational mesh was selected to ensure a balance between accuracy and computational time. A mesh independent study was conducted to identify the optimal number of elements and mesh size to accurately calculate the CFD model results while minimizing the required computational time. Multiple CFD model iterations were reviewed starting with smaller element targets with an increasing element targets until consistent results were achieved between subsequent iterations of the CFD model. The results generated by the CFD models were verified against multiple field tests completed in the LLEM.

The software Cradle SC/Tetra and SC/Stream were used to perform the numerical model of the underground explosions. Both SC/Tetra and SC/Stream have similar basic programming structures and analysis procedures. However, SC/Tetra is mostly oriented to complete numerical modeling on smaller scales using an unstructured mesh. Unstructured meshes are generally more flexible and comprise more complex geometries than structured meshes. The detail for modeling small-scale components results typically in SC/Tetra having longer processing speeds than SC/Stream due to a more sophisticated mesh generation function.

3.2 Single-Heading Full-Scale CFD Model

CFD models using both SC/Tetra and SC/Stream were calibrated and compared to existing test data from LLEM Test 469. Test 469 consisted of a single-entry test in Drift D of the LLEM test facility. A full-scale mesh model was developed for the single-entry heading consisting of a heading measuring 2.1 m (6.9 ft) in height by 6.1 m (20.0 ft) wide and 520 m (1710 ft) in length. All estimates of pressure over time from the CFD models were compared to actual test data at calibration points corresponding with field data collection points following the technical specifications of LLEM Test 469. All data collection locations consist of a single monitoring device located in the center of the drift. The distance of each data collection point from the face in the D Drift as shown in Table 1; Fig. 4. The results from the

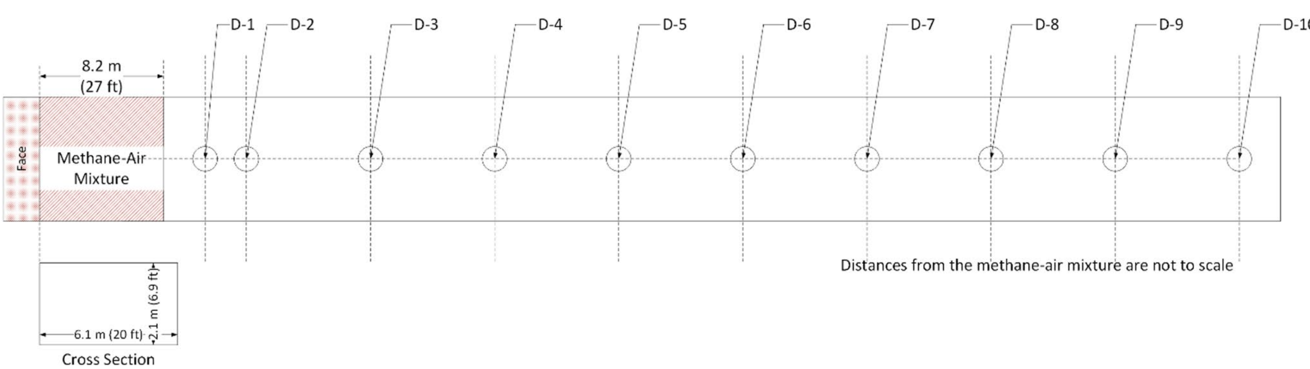

Fig. 4 Model layout of LLEM Test 469 (Based on [3]; [5]; and [21])

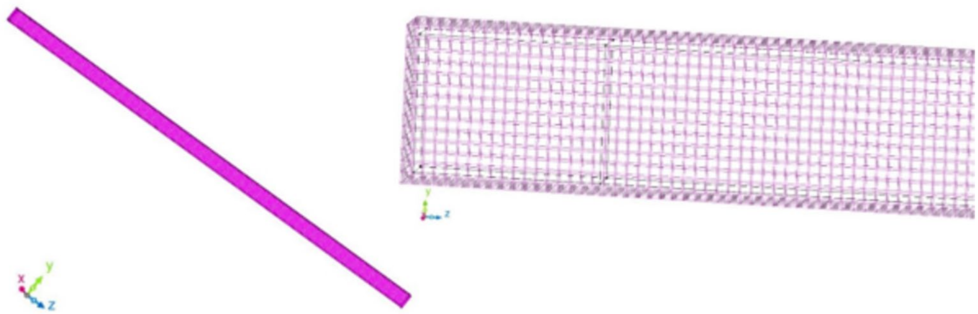

Fig. 5 SC/Tetra CFD model mesh of drift D at the LLEM test facility

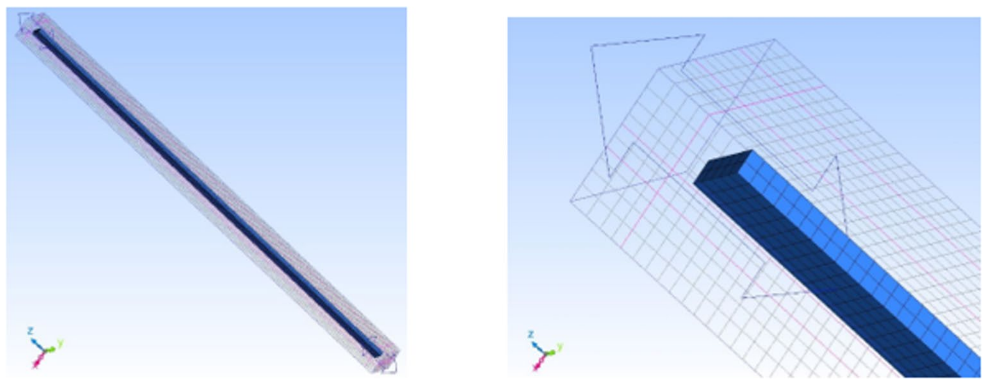

Fig. 6 SC/Stream CFD model mesh of Drift D at the LLEM test facility

comparison were used to validate the CFD modeling methods to build confidence in future, more complex modeling. The SC/Tetra and SC/Stream models are shown in Figs. 5 and 6, respectively.

The CFD models were run using density and pressure solver methods and bursting balloon initial conditions to simulate the explosive gas cloud at the end of Drift D. The pressure solver model has an initial pressure impulse of 183 kPa (26.5 psi) and an air velocity of 100 m/s (328.08 ft/s) at the edge of the explosive gas cloud. The model layout of LLEM Test 469 is shown in Fig. 4. The bursting balloon model used a density solver and contained a volume of 105 m^3 (3,708 ft^3) of a methane-air mixture containing a concentration of 9.5% methane.

3.3 Shortened Multiple-Heading Full-Scale CFD Model

LLEM Test 485 was significant in characterizing the behavior of blast air overpressure waves in an underground coal mine with multiple headings and cross sections. A considerable number of underground mine operations have more than a single heading. A CFD model based on multiple headings and cross sections would be more representative of the impacts from an underground methane explosion. Another focus of the work on shortened multiple heading full-scale models was to reduce the computational time while maintaining validated results. Multiple approaches have been developed and reviewed to help meet this objective. The various approaches consider different methodologies, such as total pressure boundaries and bursting balloon.

A shortened multiple-heading full-scale model was generated and compared against the results of LLEM Test 485 to provide confidence in future model simulations using a shortened full-scale mine network. The design for shortened full-scale model in addition to the data collection stations used to verify the model are shown in Fig. 7. Monitoring points for the model correlate to the monitoring points for LLEM Test 485 as shown in Table 2. Only monitoring points within the shortened model were considered in the analysis. The shortened full-scale network used for the model consists of the first 295 ft of the LLEM test facility. The heading dimensions for the mesh measure 2.1 m (6.9 ft) in height by 6.1 m (20.0 ft) in width with a length of 88.5 m (295 ft). The purpose of creating a verifiable shortened CFD model for a full-scale mine network is to estimate the effect of network length reduction on the pressure impulses at instrumentation locations and to support future development and testing using a small-scale network and corresponding CFD model.

SC/Tetra was used to complete a CFD analysis on the shortened multiple heading full-scale model based on the test results from the original multiple heading full-scale model. The pressure solver was selected, applying the bursting balloon initial conditions with a volume of 234 m^3 (8,264 ft^3) of methane at a concentration of 9.5%.

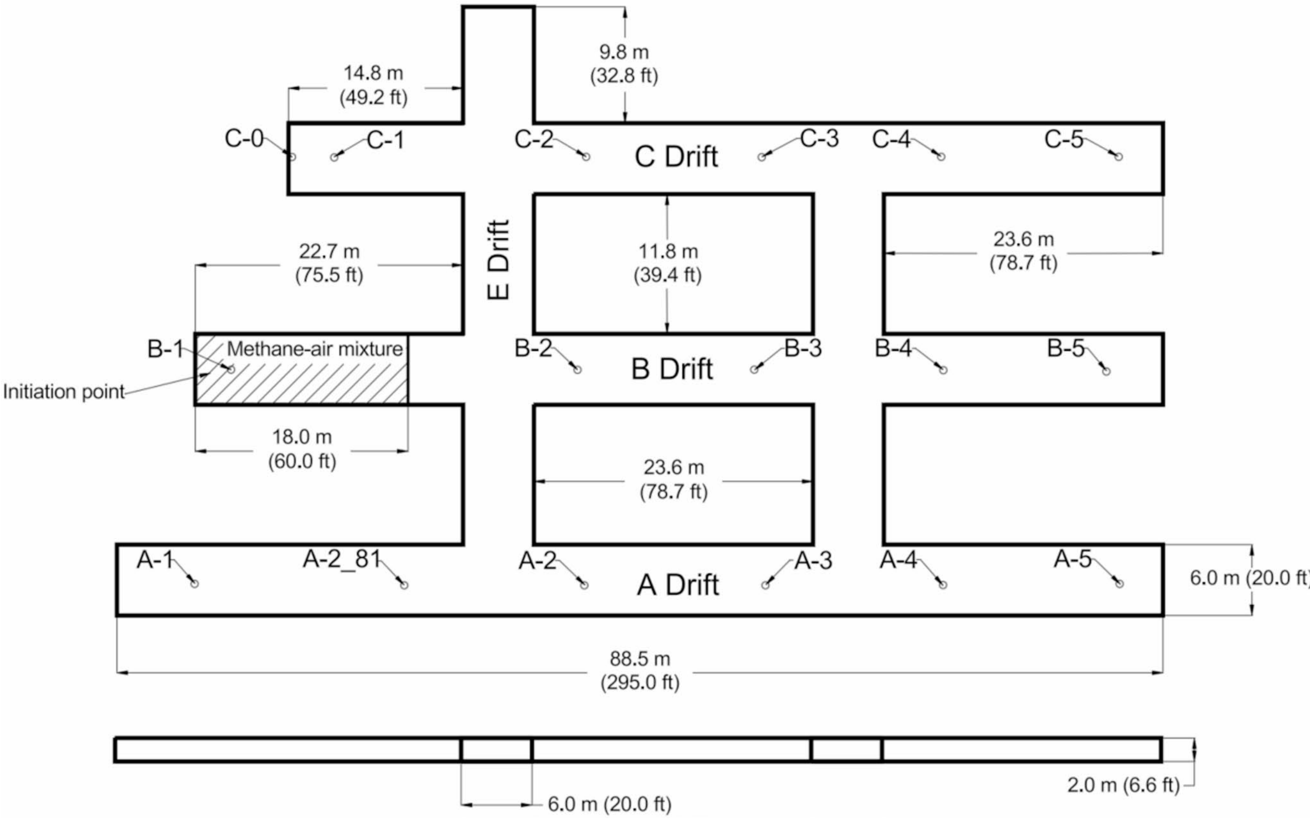

Fig. 7 Shortened multiple heading full-scale model layout [3]

4 Results and Discussion

4.1 Single-Heading Full-Scale CFD Model

The SC/Tetra model had a computational run time of approximately 1.5 h. The SC/Stream model had a computational run time of approximately 11% of the time required for the SC/Tetra model. The results of SC/Stream model were not strongly correlated to the field test data from Test 469. The SC/Stream model was determined to be out of calibration and not verified for use in future predictions and models.

The density and pressure solver models for the SC/Tetra CFD analysis show a strong correlation to field data from LLEM Test 469 distances shorter than 30 m (100 ft) from the face. For distances greater than 90 m (295 ft) and 180 m (590 ft), the computed peak pressure values are 18% and 30% lower than LLEM Test 469 field data, respectively. Comparisons of the data from the SC/Tetra models and field data from Test 469 are shown in Fig. 8. The SC/Tetra model was determined to be in calibration with single entry heading field testing and verified for use in future predictions of pressure over time at shorter distances.

The purpose of testing and verifying this model is to establish a baseline methodology to be used for developing and verifying future CFD models, specifically a shortened multiple-heading full-scale CFD model and shortened multiple-heading small-scale CFD and physical models. The verification of the single-heading full-scale CFD model against field data from LLEM Test 469 at shorter distances indicated that established methodology could be used to develop a shortened multiple-heading full-scale CFD model.

4.2 Shortened Multiple-Heading Full-Scale CFD Model

The simulation results from the shortened multiple-heading full-scale CFD model show that shortening the model network impacts the pressure readings. A comparison of pressure readings in Drift B shows relatively constant values between the shortened CFD model and LLEM Test 485. A comparison of the peak pressure impulses along the data collection stations in Drifts A, B, and C for the shortened model and Test 485 data can be seen in Figs. 9 and 10, and 11, respectively. The pressure readings in Drift A and C show a variance of 13.8 kPa (2 psi) to 34.5 kPa (5 psi) less in the CFD model compared to LLEM Test 485. Drift B shows a gradual decrease in pressure over distance, with a more significant decrease in pressure at the crosscuts. Drift

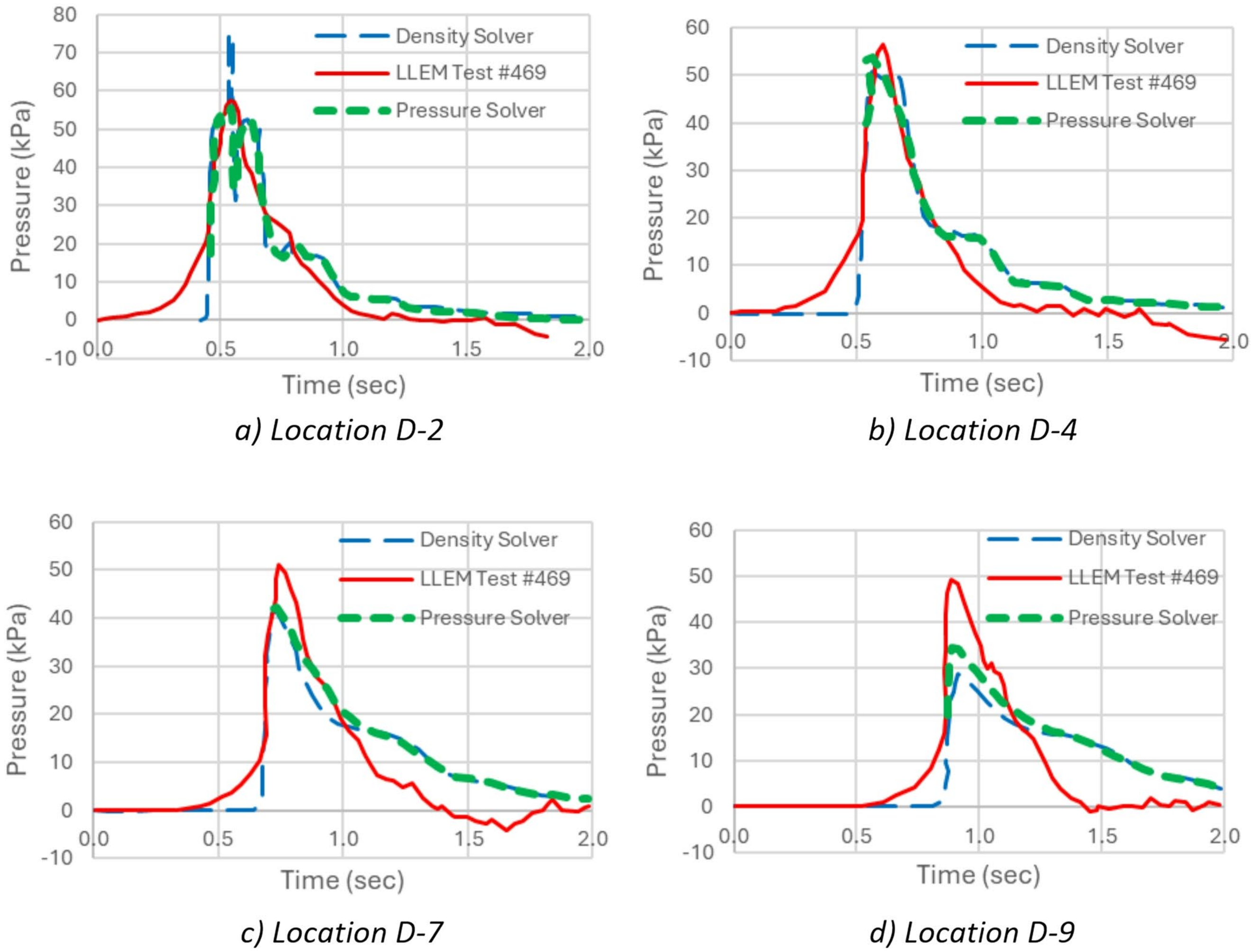

Fig. 8 SC/Tetra model predictions and LLEM test 469 data for calibration location 2, 4, 7, and 9 (based on [21])

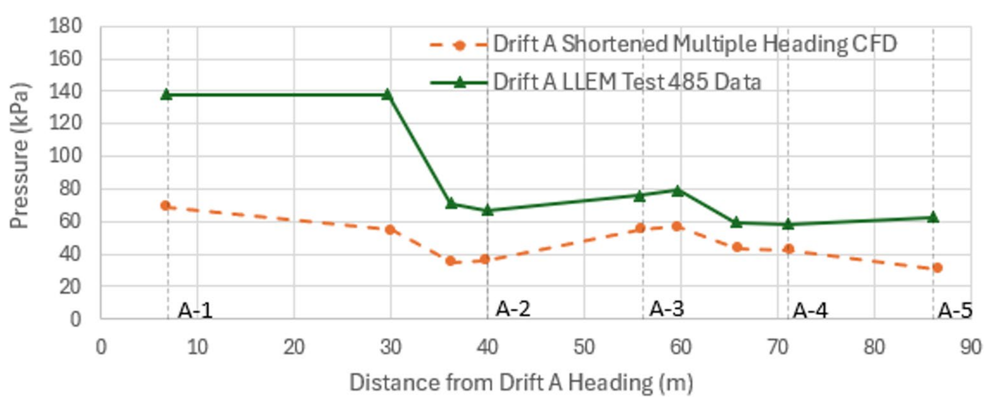

Fig. 9 Drift A peak pressure impulse comparison between shortened multiple heading CFD model and LLEM test 485 (based on [20])

A and C show an increase in pressure after the crosscuts. This increase in pressure is observed in both the CFD model and Test 485 data. The maximum difference in pressure drop between the CFD model and Test 485 data was observed at the dead ends of Drifts A and C, with a small pressure drop being observed at the end of Drift B. These results are most likely a result of reflected dynamic pressure at the dead ends of the drifts, which is not included in the presented CFD results.

The results generated from the shortened CFD model show that peak pressure values in Drift B, where the methane-air mixture was ignited, can be verified against field test data

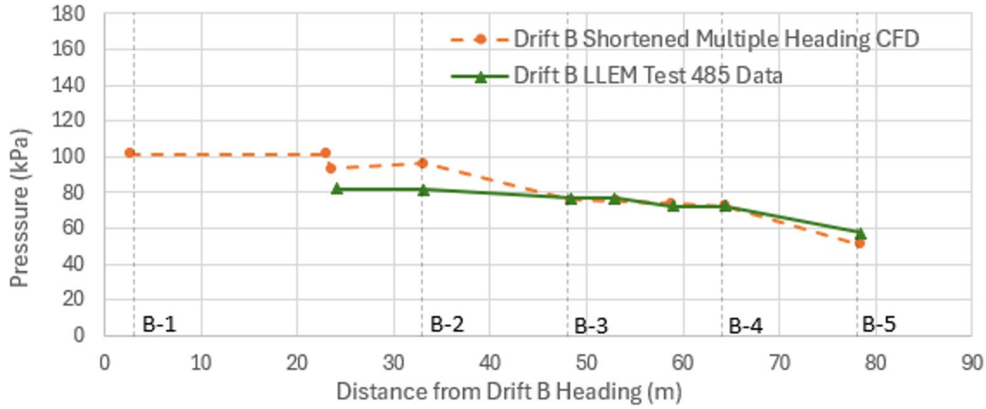

Fig. 10 Drift B peak pressure impulse comparison between shortened multiple heading CFD model and LLEM test 485 (based on [20])

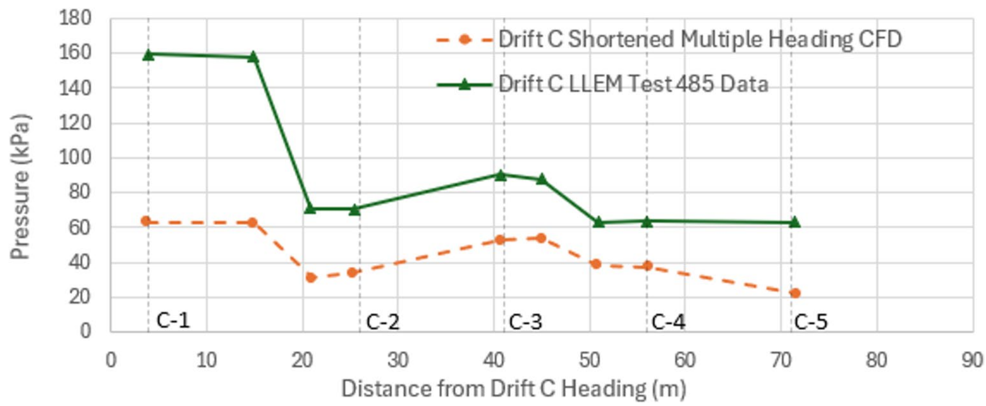

Fig. 11 Drift C peak pressure impulse comparison between shortened multiple heading CFD model and LLEM test 485 (based on [20])

from the full-length test conducted for LLEM Test 485. This indicates that the methodology used in the CFD modeling of methane-air explosions can be reliably used for predicting peak pressures for close distances in the primary drift in which an explosion is ignited. However, the results from the shortened CFD model also show that peak pressure values in Drifts A and C show similar trends but are lower than the field test data from LLEM Test 485. This may be a result of shortening the drifts in the full-scale CFD model and comparing the estimates to the full-length full-scale mine network used for field data collection. Pressure appears to not be building up in headings of Drifts A and C in the shortened CFD model. It is likely that the pressure in these drifts in venting out of the ends of the shortened model before pressure is built up to levels similar to those observed in field testing. Further development and testing of the shortened CFD model is necessary to ensure the results can appropriately be verified against field testing data. Regulators placed at the end of the shortened drifts have presented the potential for increasing the pressures observed within the mine network of the CFD model. A shortened multiple-heading small-scale CFD model and mine network are currently being developed to further test the CFD modeling methodology established as part of this research. Work on this research includes addressing the pressure loss in the model compared to the pressures observed from the LLEM Test 485 field data.

5 Conclusions

The potential for methane explosions is a significant risk in underground coal mines if safe mining conditions are not maintained or an unforeseen accident occurs. Significant effort has gone into understanding how a methane explosion impacts the underground mining environment. Part of this effort has included the development and implementation of various types of modeling to predict the impacts of potential explosions or investigate incidents involving explosions. Models allow engineers and researchers to predict, analyze, and test the pressures resulting from methane explosions in full-scale field tests.

CFD modeling has been implemented in modeling explosive pressures in full-scale single-heading and multiple-heading underground mine networks. All developed CFD models developed as a part of this research were verified against field tests completed at the LLEM test facility. The currently developed full-scale CFD models show some correlation with the LLEM field test data. The single drift model shows a strong correlation at shorter distances, whereas the multiple heading models show a strong correlation in the primary drift containing the explosion and low correlation in parallel drifts. Additional work is required to continue developing an updated, shortened multiple heading model with a stronger correlation to the LLEM Test 485 field test data. A full-length multiple-heading full-scale model should specifically be developed and tested against the LLEM Test 485 field test and shortened multiple-heading full-scale model data. Modeling using the alternative SC/Stream software should also be further considered and reviewed due to the opportunity to significantly reduce computational time and costs compared to SC/Tetra, especially when modeling larger full-scale mining networks.

Full-scale field testing often requires a significant investment in time and resources. The ability to accurately model and test underground mine explosions using a small-scale physical network would allow for future testing to be completed more safely and cost-effectively than with full-scale testing.

The results of any small-scale testing and CFD models would need to be related back to and verified against full-scale field testing and CFD models, including the LLEM field tests used as baseline data. Verifying small-scale models with full-scale test data could enable significantly more and unique explosive testing and investigation work to be completed. Small-scale physical and CFD models can be developed and tested based on the current research, especially once a more validated full-scale model is developed.

The University of Kentucky Explosive Research team is currently developing a small-scale CFD model based on the full-scale multiple heading CFD model and LLEM Test 485 data. The model will be able to be used to identify the estimated parameters and inputs to replicate the LLEM Test 485 data on a 1/10 scale. It will also be used to predict air overpressures that will result from small-scale field testing. The results of the small-scale field testing and CFD modeling can then be verified against the full-scale Test 485 data over the necessary iterations to achieve confidence in the small-scale results.

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Data Availability The data used in this paper is maintained by the University of Kentucky Explosive Research Team (UKERT) and can be made available upon special request.

Declarations

Conflict of interest All authors declare that they have no conflicts of interest.

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