Mining, Metallurgy & Exploration (2022) 39:897–916
https://doi.org/10.1007/s42461-022-00587-z

Computational Fluid Dynamics Modeling of a Methane Gas Explosion in a Full-Scale, Underground Longwall Coal Mine

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Received: 8 October 2021 / Accepted: 8 March 2022 / Published online: 27 March 2022

Abstract
Methane gas explosions are a major risk in underground coal mining operations. The severity of such explosions can range from local area damage to massive loss of miners' lives along with significant damage to mine infrastructure and ventilation controls that may lead to mine closure and loss of the entire operation. Computational fluid dynamics (CFD) modeling provides a tool to simulate methane gas explosions in underground coal mines and can help assess the potential damage of such events. The purpose of this study is to develop CFD models capable of modeling large-scale explosion in longwall mine, which can be used to study the impact of methane gas explosion on the mine ventilation. This study demonstrates the viability of integrating a combustion model into a longwall mine ventilation model to simulate methane gas explosions resulted from face ignition when the shearer is cutting the coal face. The results show that the availability of explosive gas mixtures significantly affects the resulting flame propagation and explosion pressure.

Keywords Longwall · Coal Mining · Computational fluid dynamics · Ventilation · Methane explosion

1 Introduction

Longwall face ignitions from accumulated methane gas remain one of the most common causes of methane gas explosions in underground coal mining operations. In 2017, the U.S. Mine Safety and Health Administration (MSHA) mines reported 22 cases of face ignitions during coal cutting and roof bolting operations; in 2018, there were 19 such cases. Fortunately, none of them led to a larger mine explosion. The severity of a methane explosion can be further amplified if it transitions to a coal dust explosion, as was the case in the 2010 Upper Big Branch (UBB) mine disaster, where the resulting flame propagated more than 60 km throughout the mine [1], killing 29 miners and injuring two other miners.

In U.S. longwall operations, point-type sensor methane monitors are usually installed on the body of a longwall shearer and the tailgate drive. To provide a sufficient margin of safety, the U.S. regulation 30 CFR §75.342 (Methane monitors) [2] requires the mine operator to install a methane sensor that will automatically de-energize electric equipment or shut down diesel-powered equipment at the longwall face once the methane concentrations exceed 2.0%, which is deemed sufficiently below the lower explosive limit of around 5%. U.S. regulation 30 CFR §75.323 (Actions for excessive methane) [2] also requires measurements with handheld methanometers to be made at least 0.3 m (12 inches) from the surrounding roof and rib. If these measurements detect methane in excess of statutory limits, a hazardous condition is deemed to exist. Mine operators must shut down all mining equipment and take steps to improve ventilation to dilute the methane. Despite these requirements, face ignitions continue to occur, posing a serious threat to miners and equipment. Changes in ventilation conditions and sudden outbursts of methane from the coal, floor, or roof strata can form explosive mixtures that could be ignited by the shearer cutting actions.

Computational fluid dynamics (CFD) modeling is frequently used to simulate ventilation conditions in longwall mines and to analyze airflow patterns and formation of hazardous gas mixtures, some of which are not detectable using conventional monitoring and ventilation system inspection methods. Full integration of a CFD combustion model into a full-scale longwall ventilation model is difficult

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due to the computational time and resource requirements. The purpose of this study is to demonstrate the viability of modeling a methane gas explosion in a full-scale longwall face model and the capability of predicting the impact of an explosion, by reducing the model coverage to only include area of interest and utilizing data interpolation. An improved understanding of possible explosive gas mixture locations inside the longwall face and the potential impact of methane gas explosions will aid in developing more reliable methane monitoring practices and explosion mitigation strategies to improve safety in longwall coal mining operations. For example, excessive methane concentrations are more likely when the shearer is cutting the coal face near the tailgate (TG) corner.

2 Formation of Explosive Gas Mixtures in the Longwall Face

One of the main challenges in underground longwall coal operations is providing adequate fresh air to dilute the inflow of methane gas from the active coal face. Methane concentrations must remain below the lower explosive limit, typically around 4.5% CH_4 by volume at standard ambient temperature and pressure [3, 4]. This can be difficult to achieve due to air leakage from the longwall face into the mined-out area or gob and vice versa. Different ventilation systems can significantly change the airflow patterns and movement of gas mixtures in and around the longwall face. In bleeder ventilation common in the USA, leakage to the gob is intended and common. These leakage flows, along with the natural increase of methane along the face, make the tailgate corner a critical location for methane monitoring. Depending on the face length, gob characteristics, and immediate roof caving conditions, face-to-gob leakage may amount to more than half of the supplied fresh air from the headgate (HG) in bleeder ventilation [5]. This observation is also supported by experimental studies by Gangrade et al. [6, 7] that utilized a 1/30th scale physical longwall model to show the airflow interactions between the longwall face and the gob for different gob caving characteristics and ventilation set-ups. Additionally, certain tailgate configurations or tailgate blockages from roof falls may direct face air to flow outby the face at the tailgate corner. In bleeder systems, this may entrain methane from behind the shields back into the face area [8], a condition that is suspected to have caused the 2010 Upper Big Branch explosion. In a U-type ventilation pattern, the supplied fresh air leaks into the gob at the headgate and comes back into the face at the tailgate.

With wider longwall panels, more face-to-gob leakage occurs in bleeder systems, and less air reaches the tail end of the face. Since methane continues to emanate along the face, the highest methane concentrations can be expected at or near the tailgate end of the face [9]. Other factors, such as shearer location, cutting direction, and the use of shearer cowls, also affect the flow and gas accumulation near the shearer. Without the shearer present, the bulk of the face air flow is concentrated in the area between the shield's hydraulic jacks and coal face [10]. This flow pattern shifts due to blockage by the shearer body. Near the tailgate, this blockage forces the bulk face air flow to move towards the back of the shields, resulting in higher leakage rates into the gob upwind from the shearer. The effect of this flow disturbance is most prominent when the shearer is located at the headgate or tailgate corners of the longwall face. In addition, the shearer cowls that direct the broken coal into the armored face conveyor (AFC) can increase the ignition risk by blocking and diverting the fresh air away from the cutting path and trapping the incoming methane from the coal face between the rotating drums and cowls [10]. The combination of these factors can lead to the formation of explosive methane–air mixtures around the shearer drums, especially when the shearer is cutting the tailgate corner of the longwall face.

To obtain further insight into the complex flow patterns and gas distribution in a longwall operation, several researchers have performed CFD studies modeling airflow patterns and methane distribution inside the longwall face, including [11] and inside the gob [12]. In addition, Gangrade et al. [6] and Pinheiro et al. [13] used a scaled, physical longwall model to observe the flow patterns inside the gob for different gob characteristics and ventilation scenarios. The results of these studies are useful to identify critical parameters impacting the longwall ventilation, while also identifying explosive gas concentrations in longwall faces.

Following the UBB mine explosion in 2010, Davis et al. [14] conducted several studies to simulate the flame propagation that may have occurred during the accident. However, these studies were limited to modeling the flame propagation along the mine entries. To the authors' knowledge, no combustion CFD study has been presented in literature that predicts the impact of a methane gas explosion during longwall shearer cutting operations. Methane explosion modeling in a complex mining environment, such as longwall face area, which includes component such as shields, the shearer with cowls and cutter drums, stage loader, gob plate, etc. has not been published. Therefore, it is the goal of this study to develop a comprehensive CFD longwall mine ventilation and explosion propagation model capable of investigating the impact of methane explosion resulted from face ignition when the shearer drum is cutting the coal face. This explosion scenario represents the case most found to occur during longwall coal operation.

3 Longwall Ventilation Model

Figure 1 shows the development schematic of the CFD model to simulate face ignition scenario at the longwall face.

CFD simulations were performed using the commercial software package ANSYS Fluent (v. 18.2). The longwall bleeder ventilation model, shown in Fig. 2, represented as Stage-1 in Fig. 1 is used as the base ventilation model to simulate the airflow distribution in the longwall face area.

The model panel is 150 m long and 300 m wide and the coal seam is 3 m high. The coal chain pillar dimension is 55 m by 20 m. The mine entry dimensions are 6 m by 3 m, consisting of two headgate entries, a belt entry, and two tailgate entries. The gob and fracture zone heights are 9 m and 3 m, respectively. The gob is further divided into the gob edge, transition zone, and gob center, with different porosity and viscous resistance value assigned to each zone.

The longwall face model includes the operational components typically found in a longwall operation, such as a shearer, stage loader, face conveyor, shield supports, face curtain, gob plate, and the headgate and tailgate drives. For simplification, the face curtain is modeled as wall boundary condition. A detailed view of the longwall face equipment models is shown in Fig. 3 and Fig. 4. The longwall face is supported by 152 shields. In full scale, each shield is roughly 7 m long, 2 m wide, and 3 m high. Headgate and tailgate shields are slightly longer to accommodate the headgate and tailgate drives. On the backs of each shield, there is an opening of approximately 0.28 m^2 that allows leakage air to exit and enter the face. The gob is modeled as a porous medium and divided into three zones with different porosities and viscous resistances, calculated as the inverse of permeability, based on findings by Marts et al. [12]. The gob fringe, dark gray color in Fig. 2, extends to 6 m deep inside the gob and has a 40% porosity with a viscous resistance of 1.5×10^5 m^{-2} (permeability value of 6.9×10^{-6} m^2). The transition zone, yellow color, has a 25% porosity and viscous resistance of 1×10^6 m^{-2} (permeability value of 1×10^{-6} m^2) while the fully compacted center of the gob, brown color, has a 14% porosity and a viscous resistance of about 5.0×10^6 m^{-2} (permeability value of 2.0×10^{-7} m^2). Note that the gob permeability can vary significantly for each mine, as reported by Esterhuizen and Karacan (2.0×10^{-10} m^2 to 6.0×10^{-10} m^2) [15], Yuan et al. (1.2×10^{-10} m^2 to 3.0×10^{-12} m^2) [16], Wachel (2.0×10^{-5} m^2 to 2.0×10^{-7} m^2) [17], and Marts et al. (6.9×10^{-6} m^2 to 2.0×10^{-7} m^2) [18]. The gob permeability values chosen in this study are based on the result of site study done by previous researchers in our research group [18].

For the chosen bleeder ventilation scenario, it is assumed that the tailgate corner provides a back return; that is, the return air is coursed through the first crosscut inby the tailgate. This is common practice to clear the tailgate corner of methane accumulations. The shearer is located close to tailgate corner, between shield 140 and 146, cutting towards

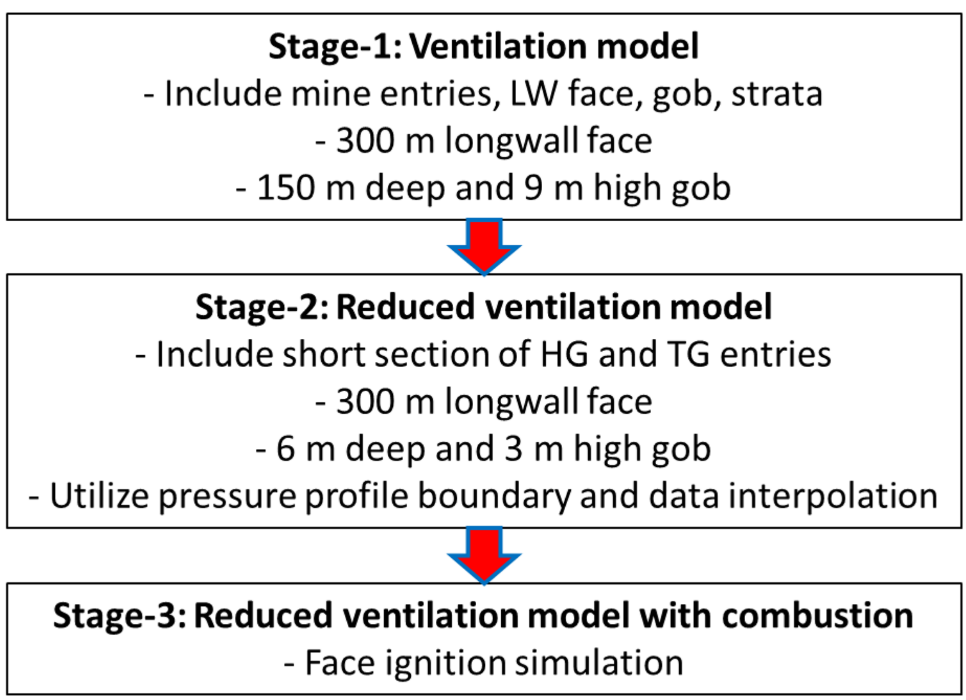


Fig. 1 CFD model development schematic

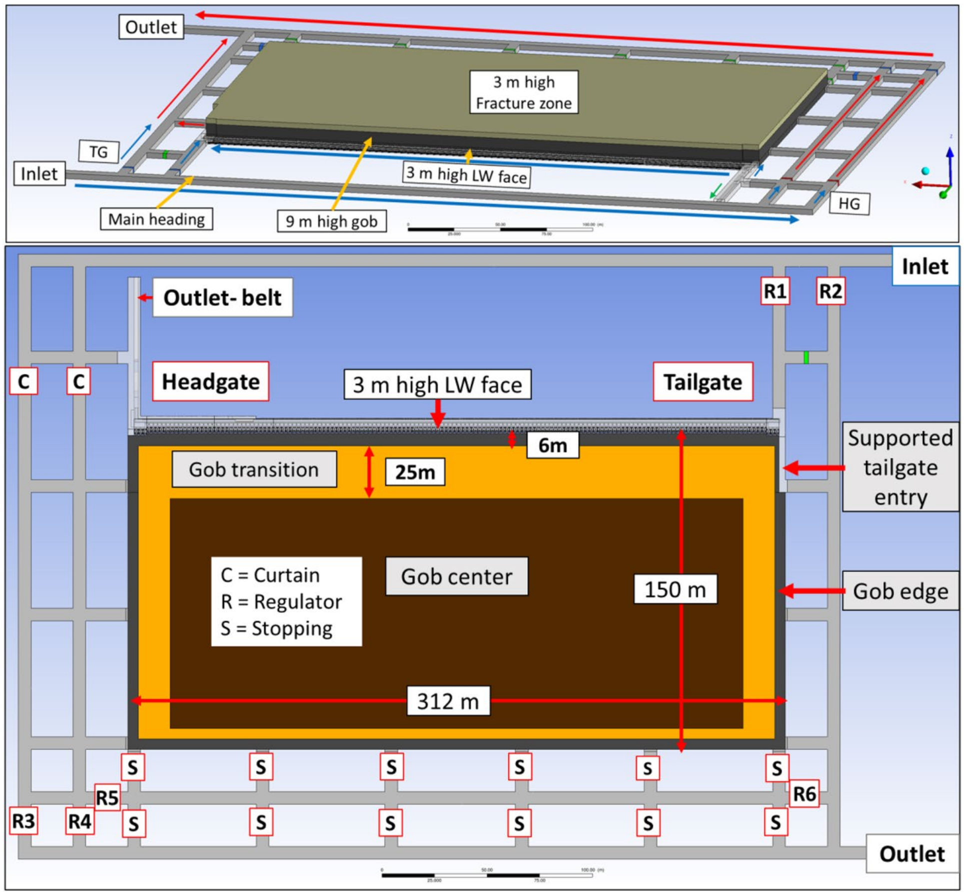


Fig. 2 Longwall bleeder model geometry

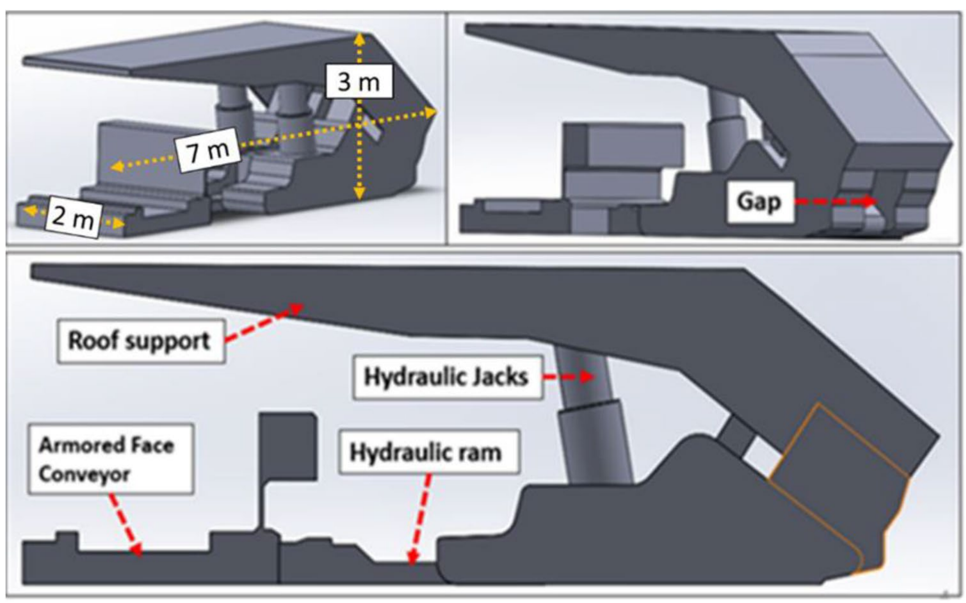


Fig. 3 Geometry of simplified longwall shield model

the tailgate. Both shearer drums are rotating at 30 RPM and shearer cowls are used.

The two headgate entries deliver a total of 55 m^3/s of fresh air to the face, a typical quantity for US longwall operations. Some of that air leaks through the headgate curtains, shown as "C" in Fig. 2, resulting in 41 m^3/s of air delivered to the face. Inby the headgate, a ventilation curtain extends from the rib of the chain pillar to shield number 3

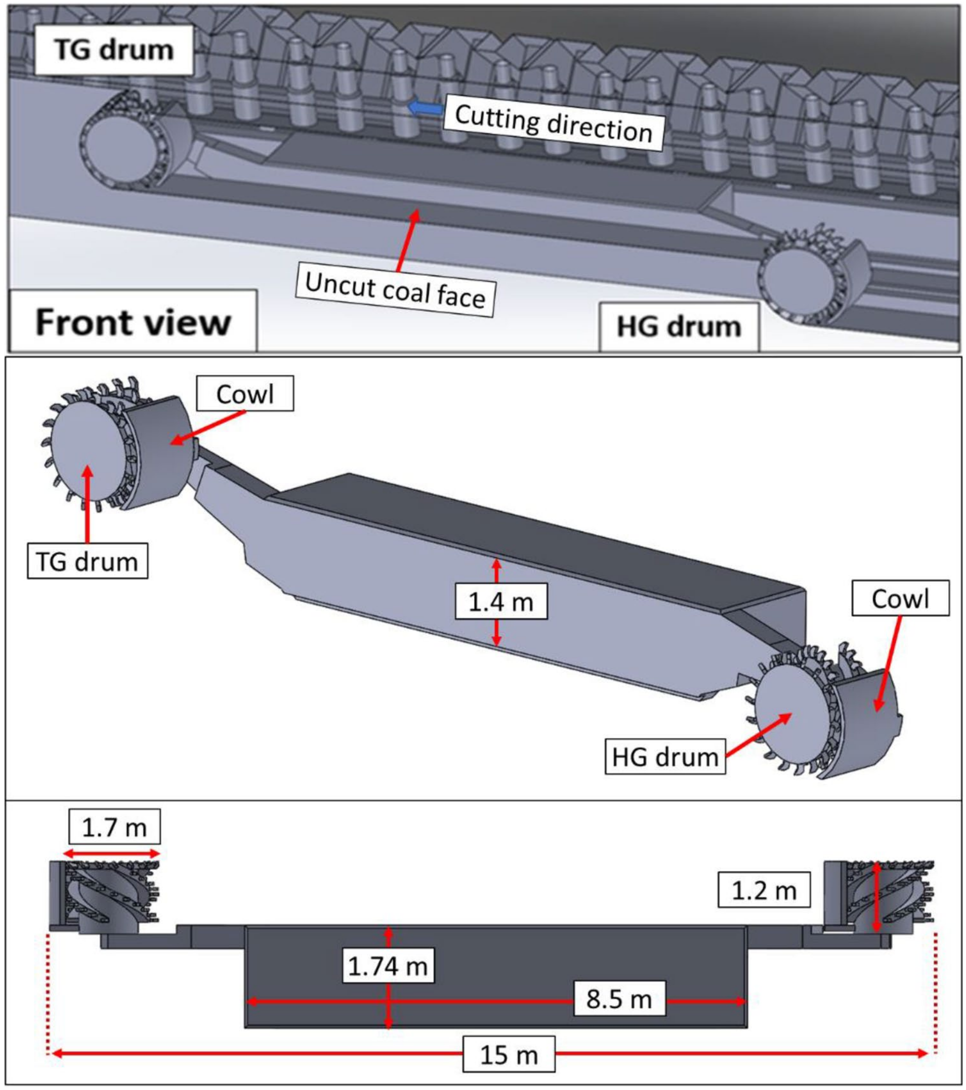


Fig. 4 Geometry of simplified longwall shearer model

to help direct the fresh air into the face. Each of the two tailgate entries outby the face is set to supply 4.7 m^3/s of fresh air. Due to the bleeder setup, most of the 41 m^3/s of face air leaks into the gob, leaving only 16 m^3/s airflow at the tailgate corner. The air flow through the bleeder entries inby the face is controlled with a series of stoppings and bleeder regulators. Regulator R3 (Fig. 2) is set to allow 4.7 m^3/s of air to pass through, while R4 and R5 are closed to force air from the headgate entries to sweep the back end of the longwall panel. Regulator R6 is kept fully open.

To simulate ignition and methane flame propagation, researchers reduced the three-dimensional ventilation model, shown in Fig. 2, to only contain the longwall face, a portion of the gob behind the shields extending up to 6 m deep and 3 m high, and a portion of the tailgate and tailgate bleeder entries. To maintain computational accuracy, pressure profiles obtained from the full-scale, steady-state bleeder model are used as both the inlet and outlet boundary conditions. Mesh sizes between 3 and 30 cm are used in the steady-state fluid flow model: a 3-cm mesh is used in high turbulence areas around the shearer drums, while a range of 3 to 30 cm mesh is used in the bulk flow regions to accurately capture the flow physics. This reduced three-dimensional model has over 31.5 million base cells before integrating the combustion model.

Limiting the model to this smaller section of the mine allows for improved cell allocation by refining the mesh in critical areas where the ignition is simulated. Once the flame expands and travels towards the model boundaries, the model will be expanded into the adjacent zones and data can be interpolated to allow flame propagation into the adjacent zones to potentially simulate the entire longwall mine model.

Table 1 lists the CFD modeling parameters and settings used with ANSYS Fluent v. 18.2 to simulate the ventilation airflow.

Table 1 ANSYS model setting for ventilation simulation

Parameter	Setting
Time	Steady state
Solver	Pressure based
Flow density	Incompressible
Species transport	Methane–air mixtures
Turbulent model	Realizable k-ε with standard wall function
Solution methods	SIMPLE scheme with second order discretization for all parameters (pressure, momentum, energy, turbulence, etc.)
Convergence criteria	1×10^{-4} for continuity and momentum, 1×10^{-3} for turbulence, 1×10^{-5} for gas species, and 1×10^{-10} for energy Grid convergence and iterative convergence was checked using velocity and methane distribution across the longwall face
Boundary condition	Pressure inlet and pressure outlet Wall roughness constant: 1; wall roughness height: 5 cm for longwall face, 20 cm for mine entries
Gob and uncut coal model	Porous medium

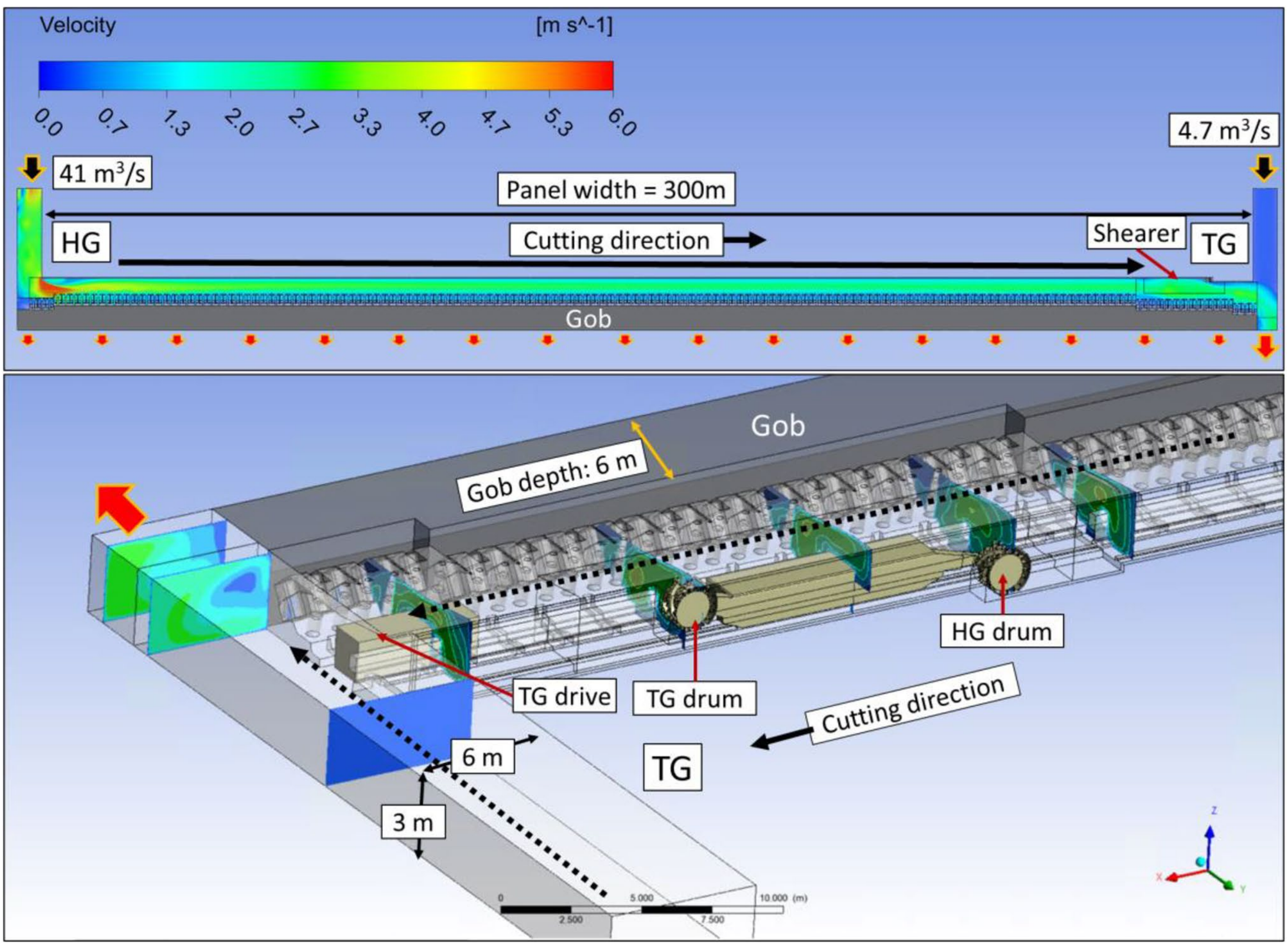


Fig. 5 Steady-state volume rendering of velocity inside longwall face from plan view (top) and velocity contour plot showing close-up view of flow around shearer drums

Figure 5, represented as Stage-2 in Fig. 1, shows the resulting reduced ventilation model, showing a plan view of air flow velocity inside the longwall face, along with a close-up, isometric view of velocity contours around the shearer drums in the tailgate corner area. The longwall bleeder ventilation scheme shown in Fig. 5 is used to simulate the gas flow distribution and subsequent ignition of explosive methane–air mixture.

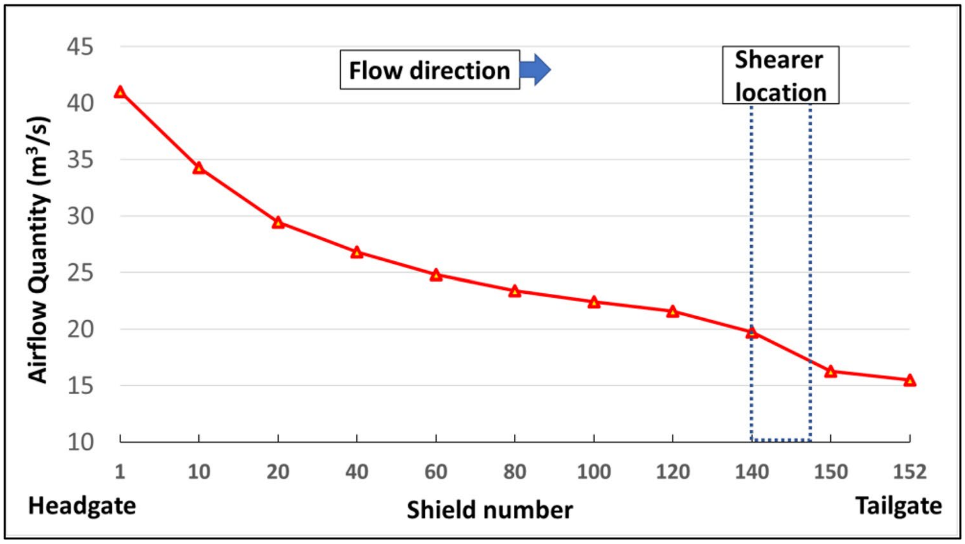


Fig. 6 Simulated airflow quantity along the longwall face

Figure 6 shows the CFD-simulated airflow quantity declining over the length of the longwall face. Significant portions of fresh air leak into the gob as the air travels across the face from headgate to tailgate. Leakage from the face into the gob increases if the gob fringe behind the shields has a high permeability, i.e., if it caves poorly and is only lightly compacted, or if the immediate roof has not been completely collapsed.

Out of the 41 m^3/s of fresh air supplied from the headgate side of the face, only around 16 m^3/s (39% of the supplied fresh air from headgate side of the face) reached the tailgate corner due to leakage from the face to the gob. This leakage is within the expected range. According to Thakur [19], for a longwall operation with a face width of 300 m, about 70% of supplied fresh air may leak into the gob by the time it reaches the tailgate corner. A study using tracer gas by Krog et al. [20] on a 300-m longwall face reported that only about half the airflow reached the tailgate bleeder entry, while the rest leaks through the gob behind the shields.

For the methane inflow source, this study only considers methane emanating from the uncut coal face around the shearer location. To simulate methane emanating from the coal face, a 20-cm-thick, porous medium is modeled behind the coal face. The source term method is used to supply 0.07 m^3/s of pure methane gas, simulating methane flowing from the cleats in the uncut coal around the shearer drums. This amount of methane resulted in a CFD model that predicts close to, but still less than 2% CH_4 at the shearer body and TG drive where methane sensors are usually installed in real mine operation. The amount of incoming methane gas is within the expected cumulative longwall face methane emission for 300-m long active face based on the study by Schatzel et al. [21]. Figure 7 and Fig. 8 show volume rendering of the methane mole fraction around the shearer for this

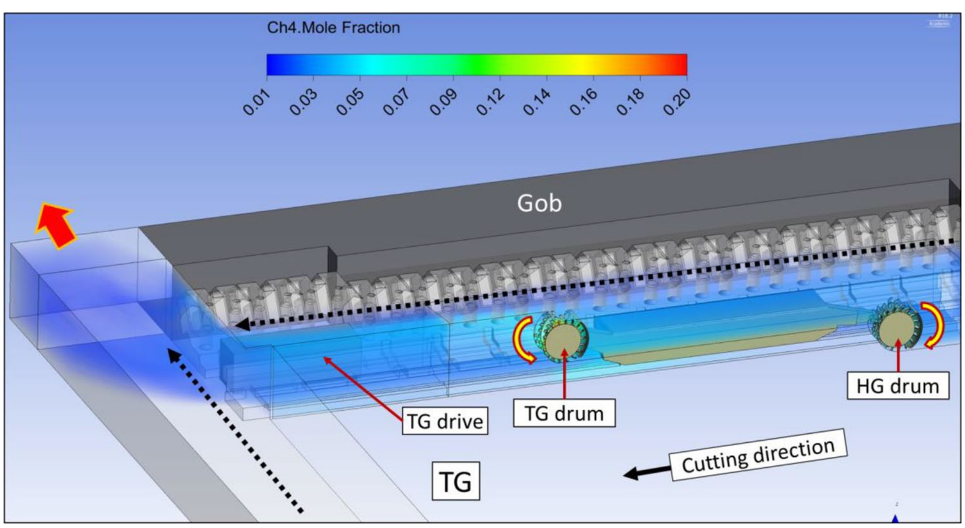


Fig. 7 Steady-state volume rendering of methane mole fraction around shearer from front view

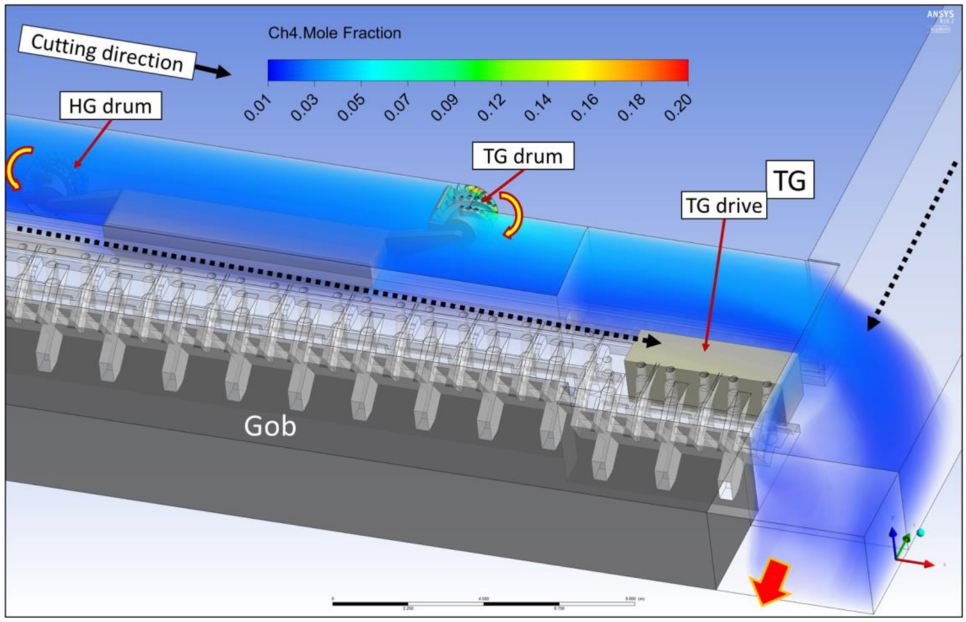


Fig. 8 Steady-state volume rendering of methane mole fraction around shearer from back view

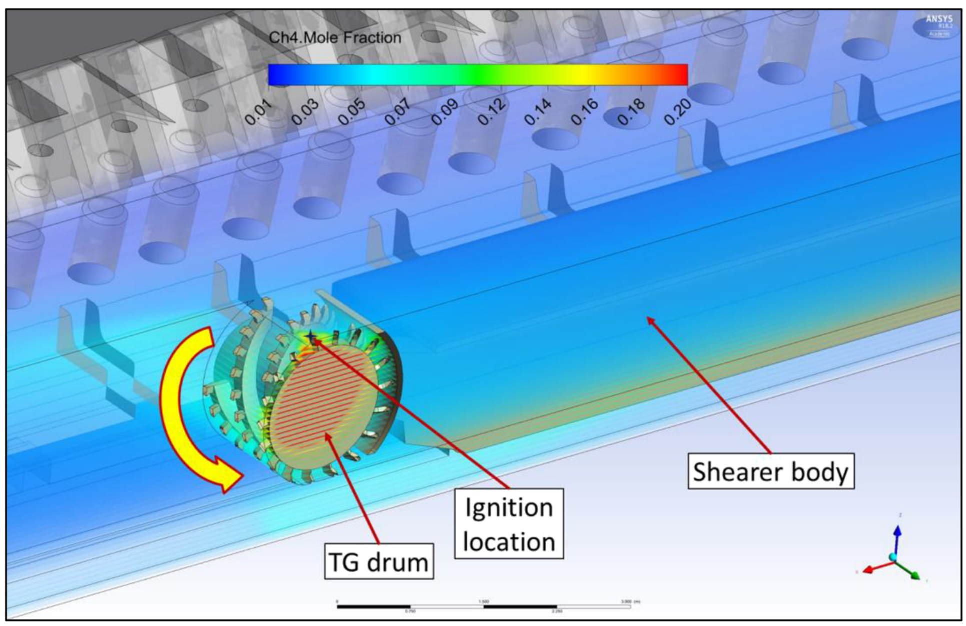


Fig. 9 Steady-state volume rendering of methane mole fraction around shearer drums and ignition location

ventilation scenario, while Fig. 9 shows the assumed ignition location at the top of tailgate side cutter drum. The underlying assumption is that this drum cuts into the sandstone roof where cutter bits leave hot, incendive metal smears [22]. The shearer drums are modeled as rotating drums by assigning rotating wall boundary condition with 30 RPM rotational speed, which is discussed in more detail in Juganda [23].

Figure 9 shows methane accumulations between the tailgate drum and the uncut coal as well as between the tailgate drum and the cowl while the shearer is cutting towards the tailgate. For this scenario, it is assumed an ignition occurs at the coal face, near the roof, while the tailgate drum is cutting the coal face. It should be noted here that the space between the cutter and the cowl is usually filled with coal but when the shearer movement stops and the dust control sprays on the cutter drum are not working properly, this area quickly clears and will fill with explosive methane–air mixture. This condition is believed to be one of the possible ignition scenarios in the Upper Big Branch mine explosion in 2010 [1].

This ignition location was chosen to represent a possible face ignition scenario during the headgate-to-tailgate cutting scenario. In the model, the shearer drums rotate with a fully developed flow. At the onset of ignition, the drum rotation at 30 RPM (~2.8 m/s linear velocity) is significantly slower compared to the pressure wave generated during the simulated methane combustion event; thus, the drum rotation is switched off and the drums are treated as stationary to simplify the model during the explosion simulation. Considering the time scale of the explosion, on the order of milliseconds, the continuous movement of the shearer and rotation of the drums does not have a significant impact on the pressure waves generated from the methane ignition. During the first 5 ms, the cutter bits will advance a distance of ~14 mm, less than half the diameter of a cutter pick.

4 Integration of the CFD Combustion Model

This section represents Stage-3 in Fig. 1. Methane combustion modeling is computationally intensive and has more restrictions on mesh size and quality than modeling non-reactive fluid flow. For example, laminar methane–air flames have a flame thickness on the order of 1 mm and a quenching distance of 2–3 mm for a stoichiometric flame (9.5% methane by volume) at 300 K and 101 kPa [24, 25]. For modeling purposes, the mesh size should be less than a millimeter to resolve the chemical reaction zone and not larger than a few millimeters to resolve the temperature and specifies gradients immediately upstream of the reaction zone in order to fully resolve the propagation of the flame front. The fluid flow boundary layers and other key fluid flow features in full-scale ventilation model are much larger than the flame thickness; thus, the base mesh for the fluid flow can be larger than what is required to fully resolve the flame reaction front. Therefore, mesh adaptation is important to ensure model accuracy under acceptable computational times. To resolve the flame front propagation, the model uses 3 levels of mesh adaption on the temperature gradient resolving the flame front each time step. This method has proved useful when simulating methane combustion in both small and large domains [26, 27].

After steady-state simulation of the ventilation conditions, the model settings are changed to simulate a transient combustion event. The model settings for ignition and subsequent methane flame propagation are shown in Table 2 and the two-step methane–air reaction mechanism settings are detailed in Table 3 and Table 4. Reaction parameters 1 and 2 required for the Arrhenius rate equation were taken from Dryer and Glassman [28]. When simulating the combustion event, the model is run as transient to understand the time-varying nature of the methane flame and pressure wave propagation. The turbulent model used for modeling flame interaction with obstacles (i.e., shearer) is a standard k-ω with low Reynolds corrections and shear corrections. The other major change is the change from incompressible to compressible flow which is necessary for accurate simulating methane deflagrations. Finally, it is important to note the changes in time steps as the simulation progresses. A time step of 10 μs was chosen to resolve the reaction kinetics during the early stage of flame expansion. This time step is increased to 20 μs and 40 μs after the flame propagates away from the shearer into the region with the coarser base mesh to speed up the simulation time.

Ignition was initiated using the ANSYS Fluent Spark Model (v18.2) with the following settings:

Table 3 Arrhenius two-step equation for methane–air two step reaction [28]

	Reaction
1	$CH_4 + 1.5O_2 \rightarrow CO + 2H_2O$
2	$CO + 0.5O_2 \rightarrow CO_2$
3	$CO_2 \rightarrow CO + 0.5O_2$

Table 2 ANSYS Fluent v 18.2 model settings for methane combustion

Parameter	Setting
Time	Transient
Solver	Pressure based
Turbulent model	Standard k-ω model, with low Reynolds number corrections and shear flow corrections
Species transport	Volumetric reactions, finite rate chemistry, laminar flame speed theory
Chemical mechanism	Methane–air 2-step mechanism
Flow density	Compressible
Solution methods	PISO scheme with first-order discretization
Convergence criteria	1×10^{-4} for continuity and momentum, 1×10^{-3} for turbulence, 1×10^{-5} for gas species, and 1×10^{-10} for energy
Boundary condition	Pressure inlet and pressure outlet profile, adiabatic wall
Time step	10 μs until 20 ms; 20 μs for 20–50 ms; 40 μs onward, with 200 iterations per time step
Adaptive meshing	3 levels refinement based on temperature gradient every time step

Table 4 ANSYS Fluent 2-step methane–air chemical mechanism settings. R stands for reactant and P stands for product. Parameter values for reactions 1 and 2 are taken from Dryer and Glassman [28]

Reaction	Molecule	Reaction order	Path	A Pre-exponential factor (kmol/m^3)	E_a Activation energy (J/kg-mol)	b Temperature exponent
1	CH_4	0.7	R	5.01×10^{11}	2×10^8	0
1	O_2	0.8	R			
1	CO	0	P			
1	H_2O	0	P			
2	CO	1	R	2.24×10^{12}	1.7×10^8	0
2	O_2	0.25	R			
2	CO_2	0	P			
2	H_2O	0.5	P			
3	CO_2	1	R	5×10^8	1.7×10^8	0
3	CO	0	P			
3	O_2	0	P			

- Ignition energy, $E_{ign}=60$ mJ
- Ignition energy duration = 1 ms
- Initial kernel radius = 2 cm
- Laminar kernel expansion

5 Modeling Results and Discussion

Figure 10 shows a volume rendering of the initial explosion temperatures and pressures from an ignition near the tailgate drum. The wave front from the explosion overpressure is expanding more quickly than the flame front. This is important because the pressure wave preheats the air ahead of the flame front, which will enhance the flame propagation velocity leading to a more violent explosion. In addition, these overpressure waves also have the potential of coalescing into a single shock wave. If this happens, the shock wave or waves may interact with each other or nearby surroundings and potentially transition the explosion from a deflagration to detonation which can be much more devastating to nearby mine equipment, structures, and miners [29].

Figure 11 and Fig. 12 show volume renderings of temperature and total gauge pressure at different time instances. The brown streamlines in Fig. 12 represent the airflow streamlines in the longwall face.

Results show that initially the flame expands in all directions, but at 100 ms the flame begins to expand preferentially towards the headgate side of the face. At this same time, the pressure waves are beginning to divert the airflow away from the face. The results show that the ignition produces multiple pressure waves. The snapshot at 200 ms clearly shows that the overpressure from the explosion is sufficient to divert face airflow into the gob area where it can mix with the available methane, creating new or expanding explosive mixtures inside the gob area. In addition, diverting the flow from the shearer drums reduces the available fresh air to dilute the methane around the drums, potentially creating an environment which can lead to secondary or tertiary explosions.

Figure 13 shows the flame front propagation velocity over time. To analyze the flame front propagation velocity, multiple lines are created using the ignition location as the base. Several parameters such as temperature gradient and kinetic rate of reaction are compared.

Based on the result, higher velocity is observed when the flame propagating in the confined space between the picks, uncut coal, and shearer cowl, around the shearer tailgate drum area. After around 85 ms, the flame front exits the tailgate drum area to a more open space, and the speed decreased significantly to around 5 m/s. This decrease in the flame speed may also be attributed to the flame propagating from the explosive mixture region close to the coal face, into the fuel-lean mixture region that is not adequate to sustain flame propagation, as shown in Fig. 14. This would change if the volume was larger and if the explosive mixture extended out past the drum.

Based on the magnitude of the flame speed and the resulting overpressure, this case represents an early stage of a small face ignition during the shearer cutting operation. It is important to note that different ventilation scenario and methane distribution can significantly impact the resulting flame speed and overpressure. To test this, similar simulation was done using a second model with larger explosive gas zone (EGZ), as shown in Fig. 15 and Fig. 16. In the second case, the amount of methane inflow from the coal face is doubled, from 0.07 m^3/s to 0.14 m^3/s, while maintaining the same amount of fresh air supplied from the headgate side of the longwall face. This second scenario represents the case when the sensors on the shearer and on the tailgate drive both fail to detect high concentration of methane.

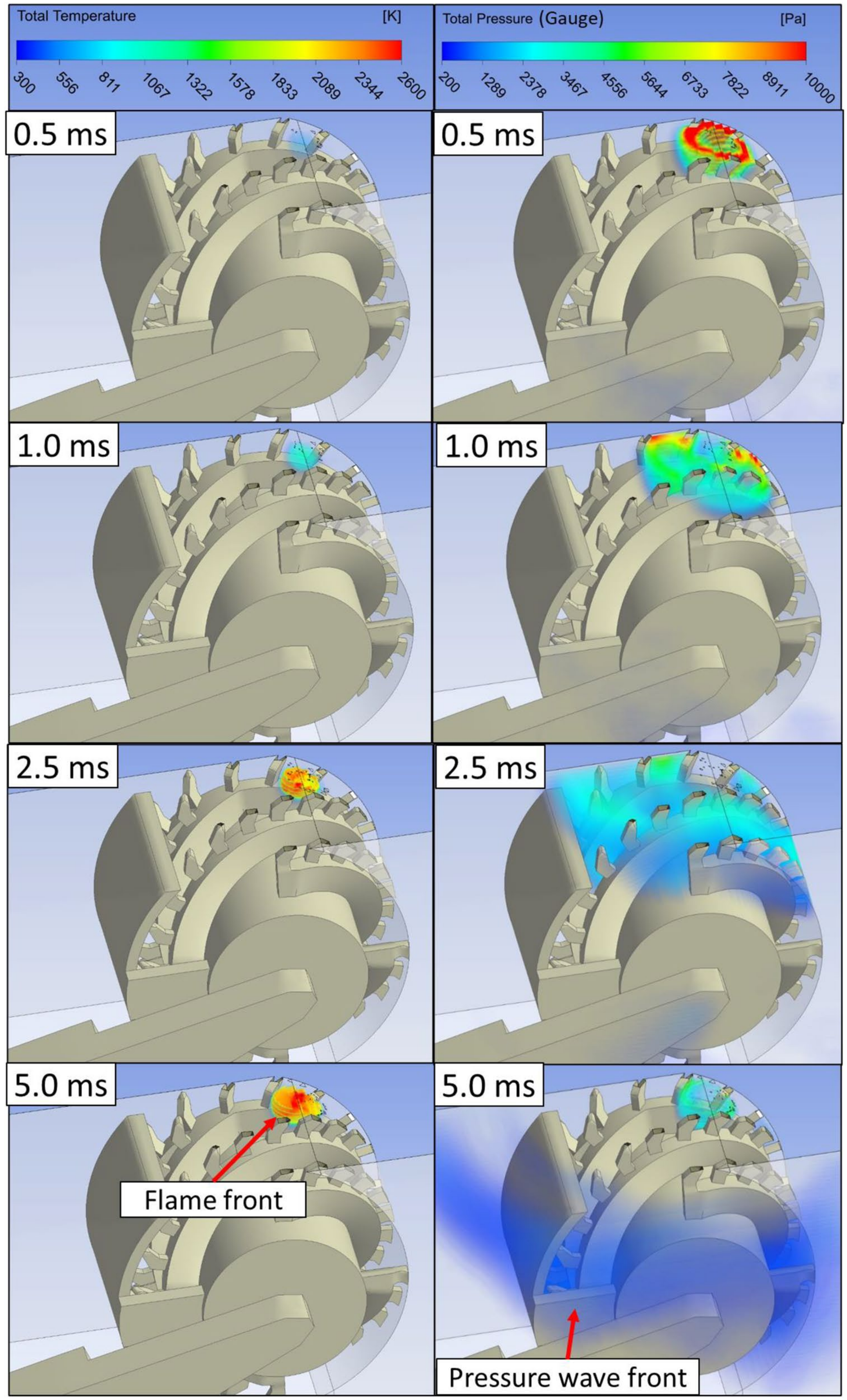


Fig. 10 Volume rendering of the temperature and overpressure showing the early stages of flame propagation

Figure 17, Fig. 18, Fig. 19, and Fig. 20 show the comparison of flame propagation for the two cases. Note that the ignition location for case-2 is slightly offset to simulate the start of ignition where the methane concentration is 9.3% by volume, similar starting condition with the case-1.

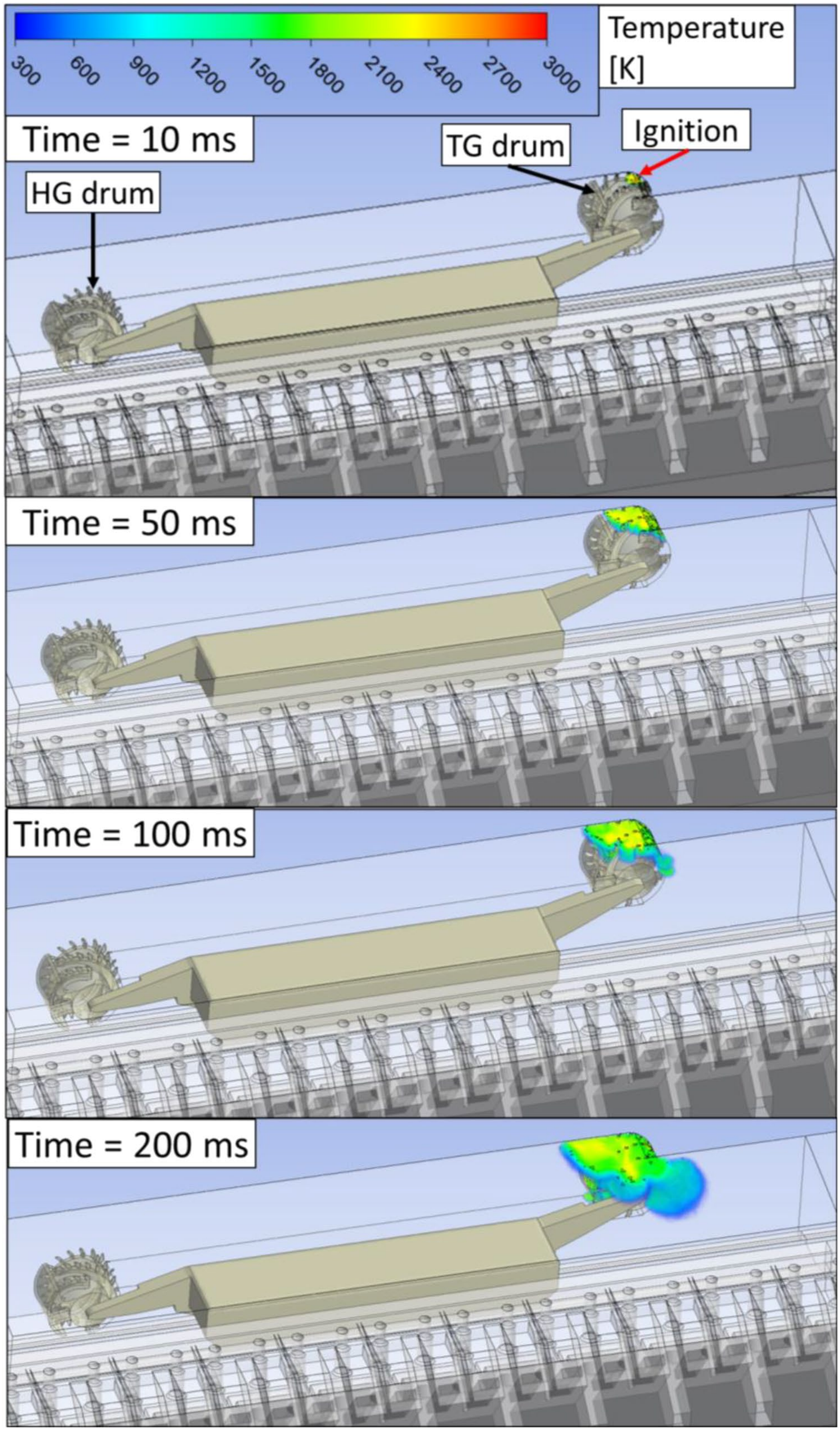


Fig. 11 Volume rendering of temperature showing flame propagation at different time instances

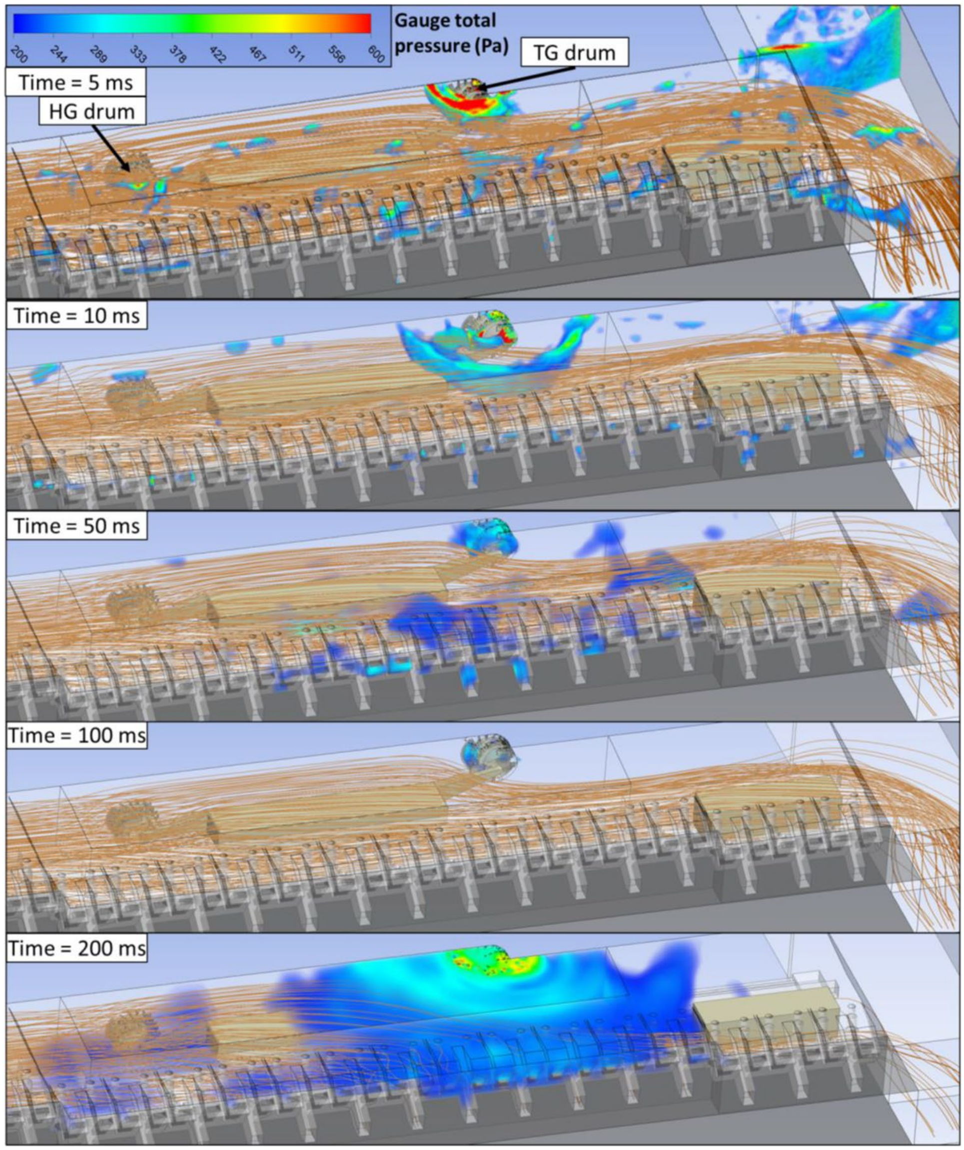


Fig. 12 Volume rendering of total gauge pressure showing ignition and explosion overpressure. Brown lines represent the streamlines of airflow in the longwall face

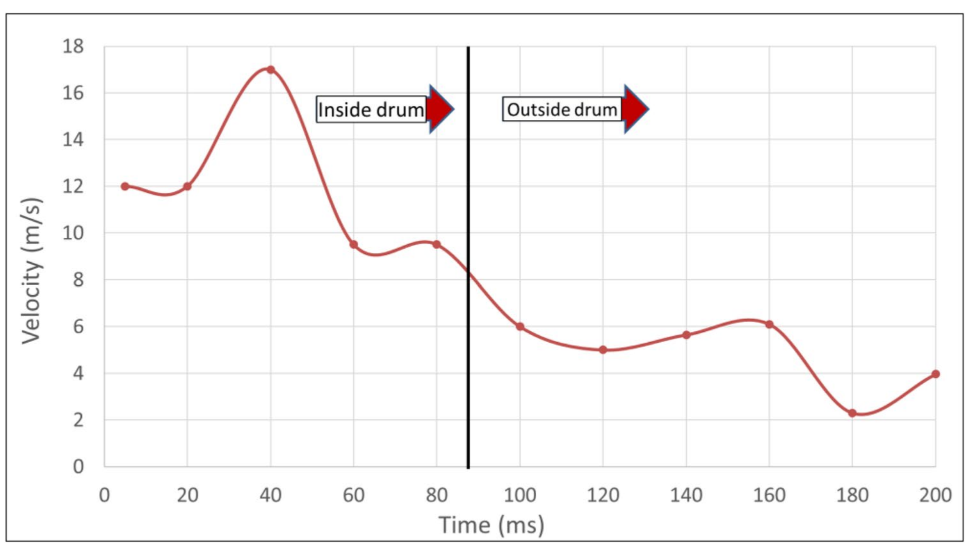


Fig. 13 Flame front propagation velocity over time based on kinetic rate of reaction

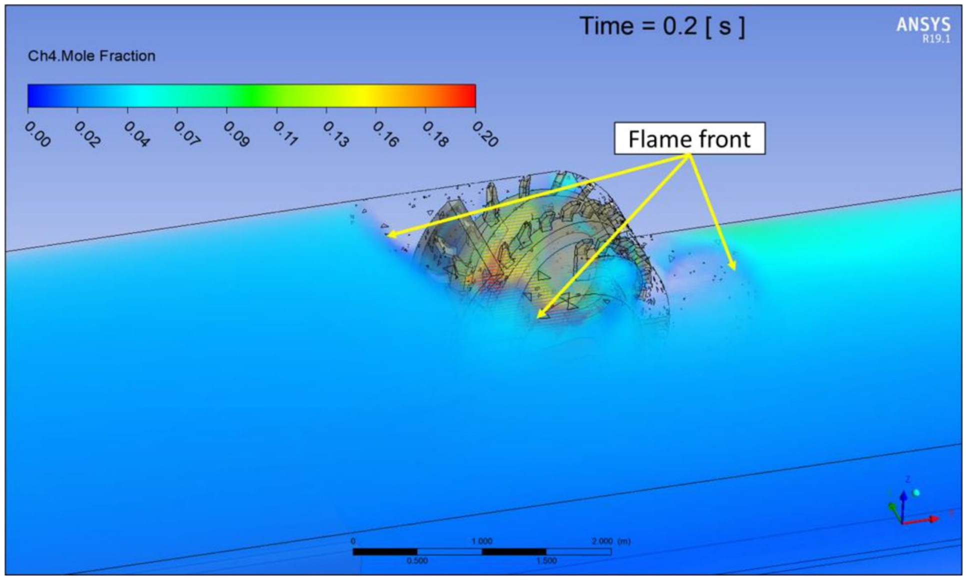


Fig. 14 Volume rendering of CH_4 mole fraction, showing flame propagating into fuel lean mixtures at 200 ms

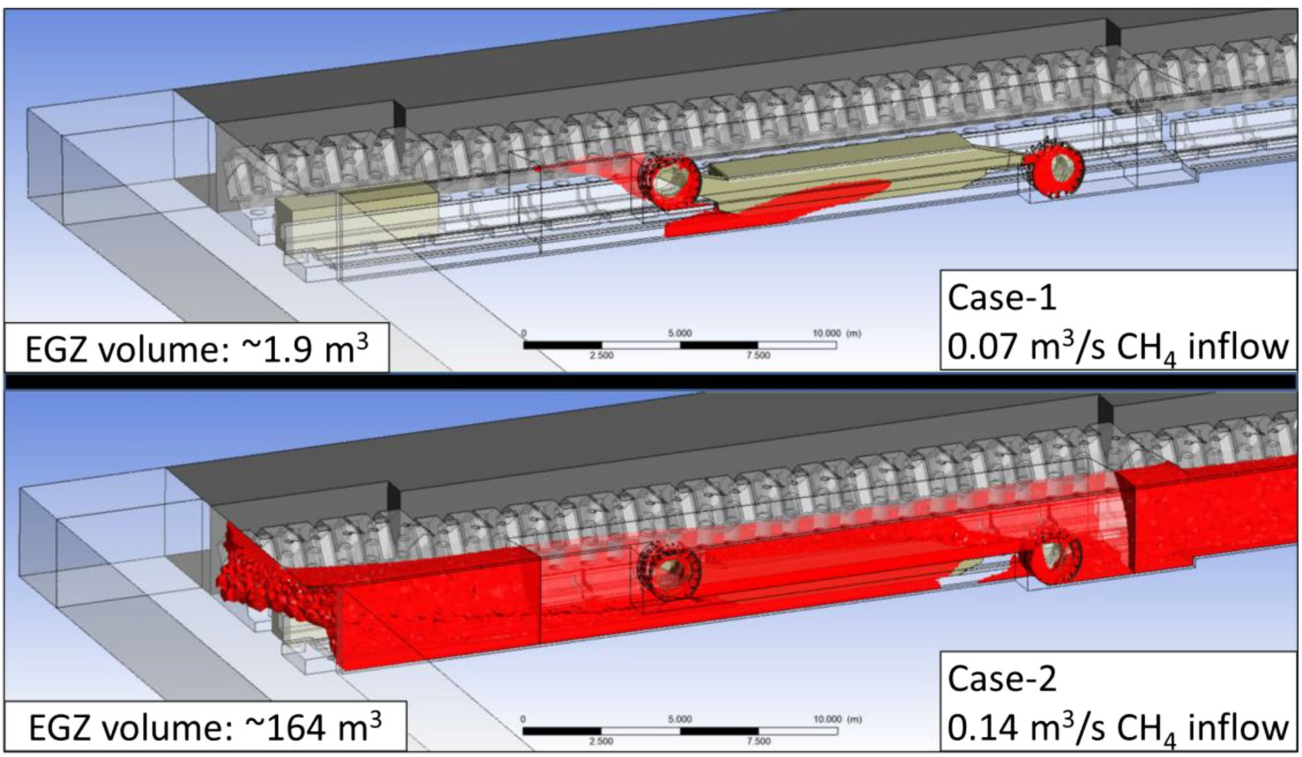
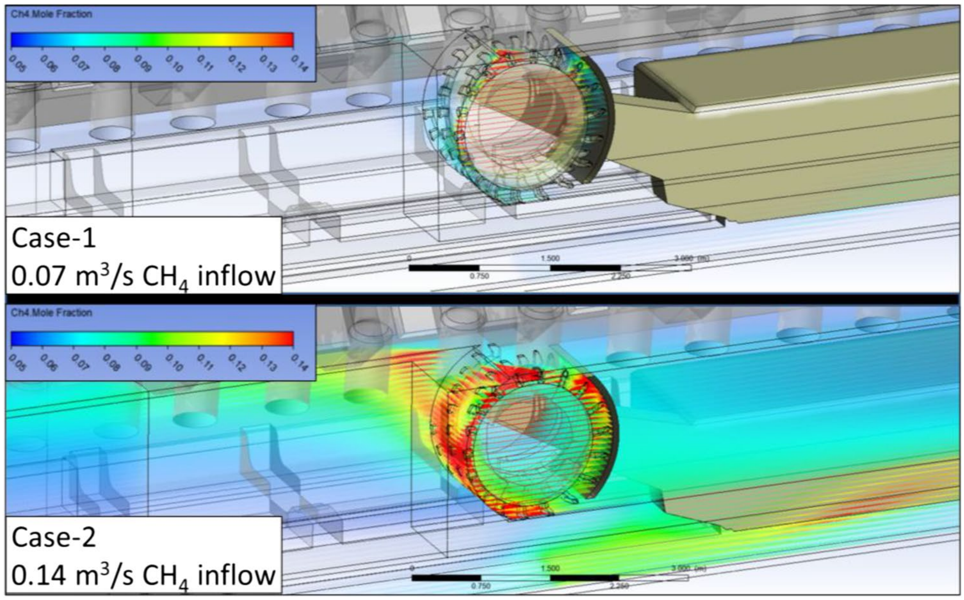


Fig. 15 Comparison of explosive gas zone volume for the two cases. The red-colored cloud represents explosive gas mixtures with CH_4 mole fraction value between 5 and 14%

Figure 21 shows comparison of the flame front propagation velocity over time.

The results comparison clearly shows the impact of the available explosive gas zones on the resulting flame propagation, with the second case showing significant increase propagation velocity and overpressure from less than 1,000 Pa to greater than 6,000 Pa within the 120-ms time frame after the ignition, as shown in Fig. 22. Similar flow pattern with case-1 can be observed in case-2; at 40 ms, the resulting pressure waves already divert the incoming airflow

Fig. 16 Comparison of methane distribution around the tailgate shearer, showing volume rendering of CH_4 mole fraction



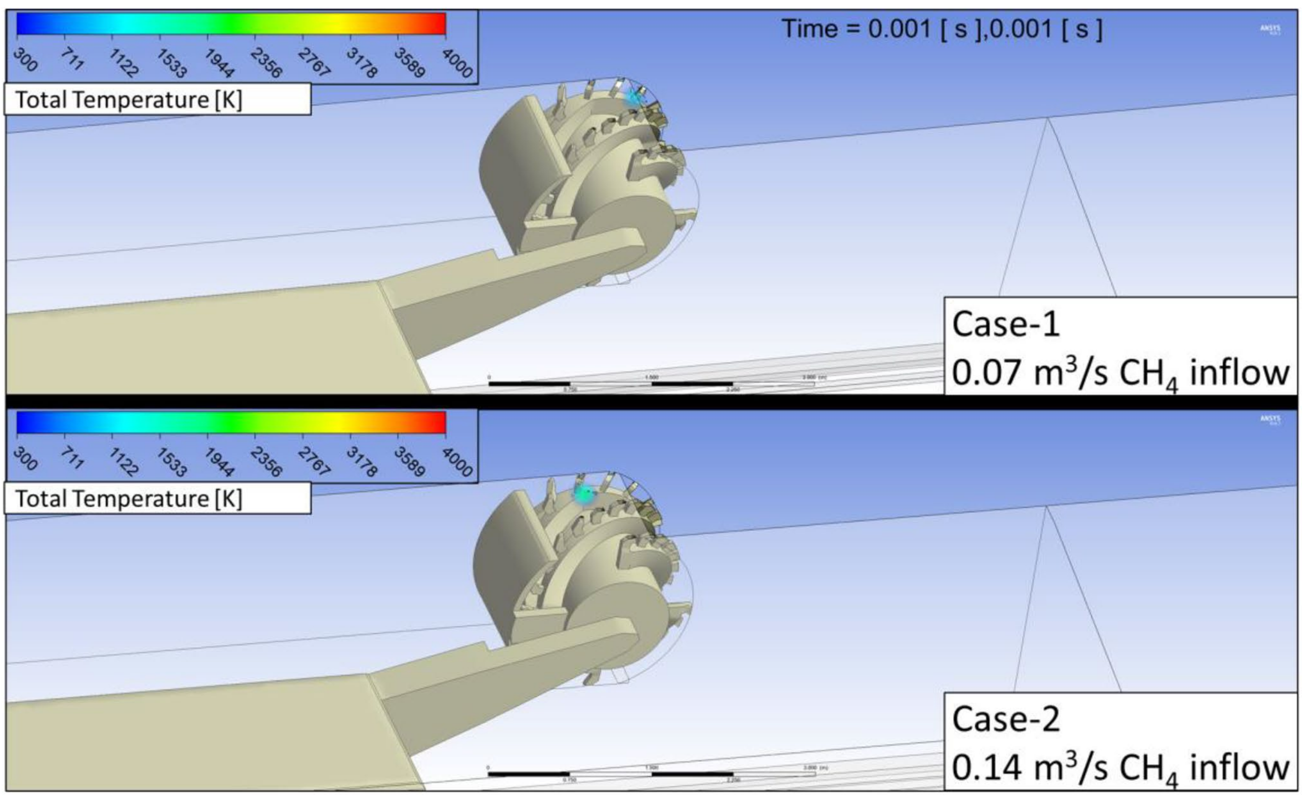


Fig. 17 Volume rendering of total temperature showing flame propagation at 1 ms

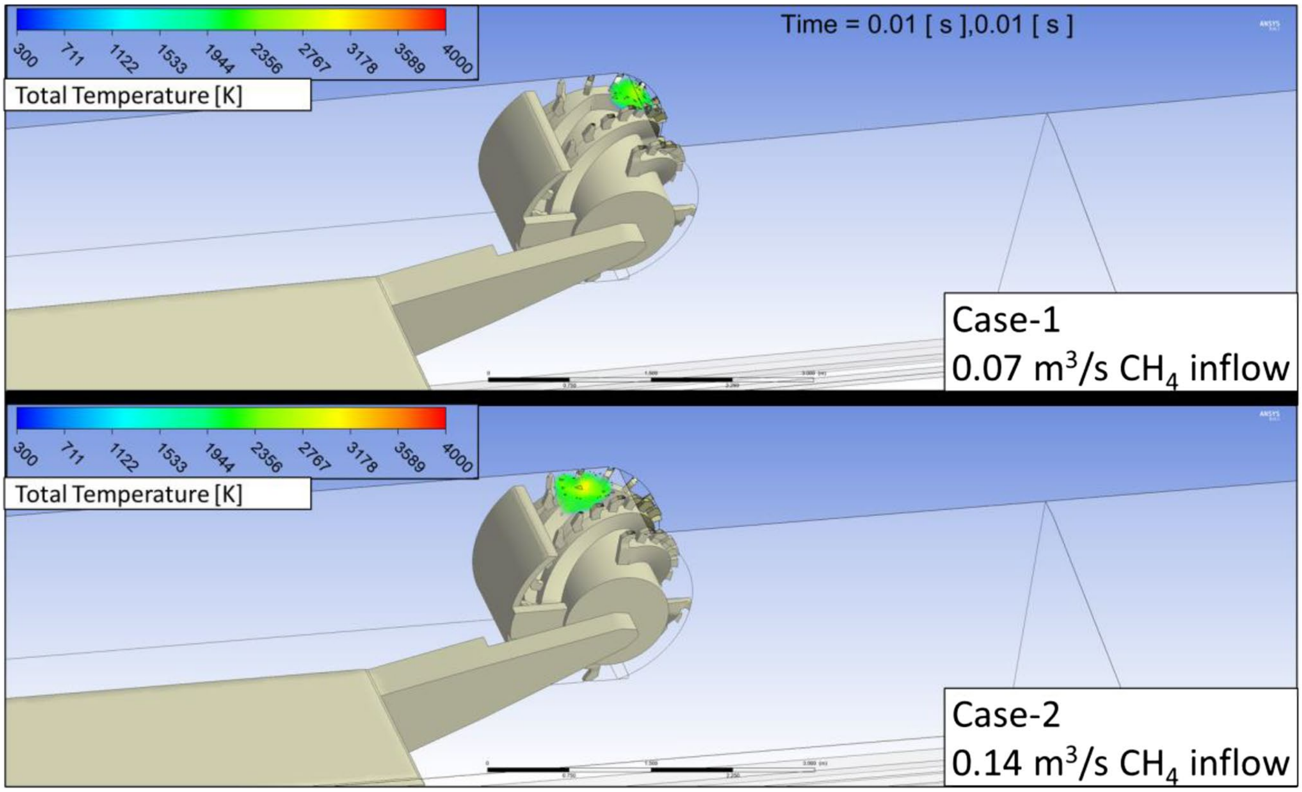


Fig. 18 Volume rendering of total temperature showing flame propagation at 10 ms

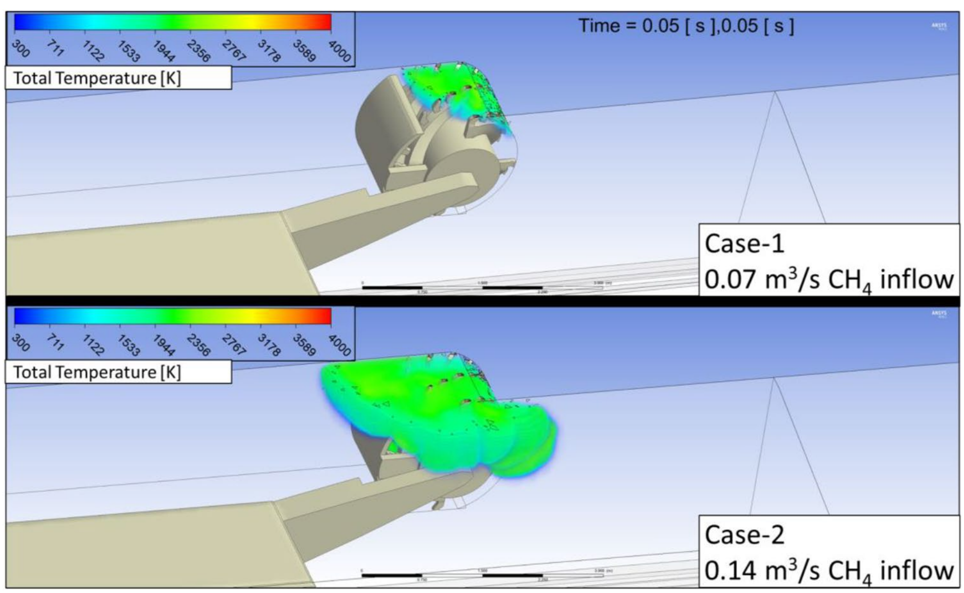


Fig. 19 Volume rendering of total temperature showing flame propagation at 50 ms

from headgate side of the face towards the gob. The snapshot at 60 ms shows that the supplied fresh air is no longer reaching the tailgate corner of the longwall face. The impact of the explosion is more severe in case-2 due to having larger volume of explosive gas mixtures available around the ignition location.

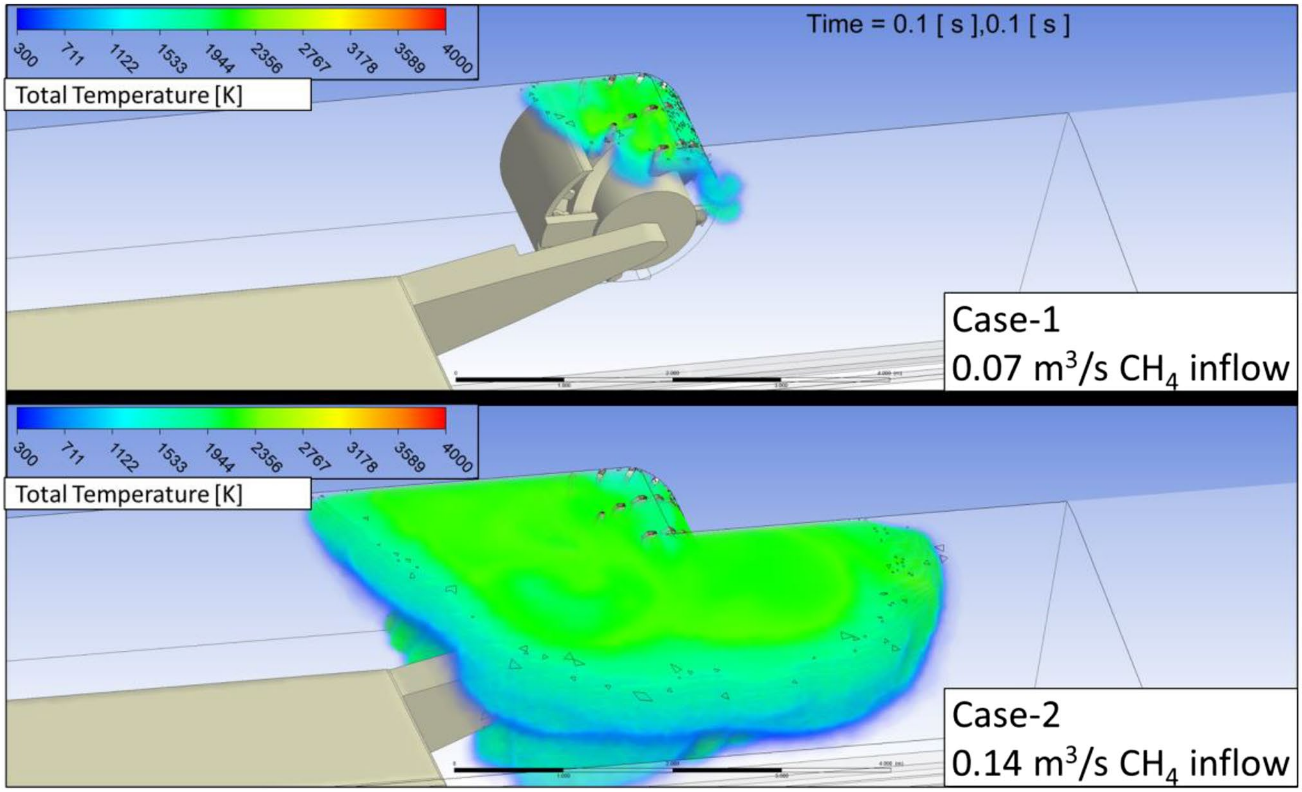


Fig. 20 Volume rendering of total temperature showing flame propagation at 100 ms

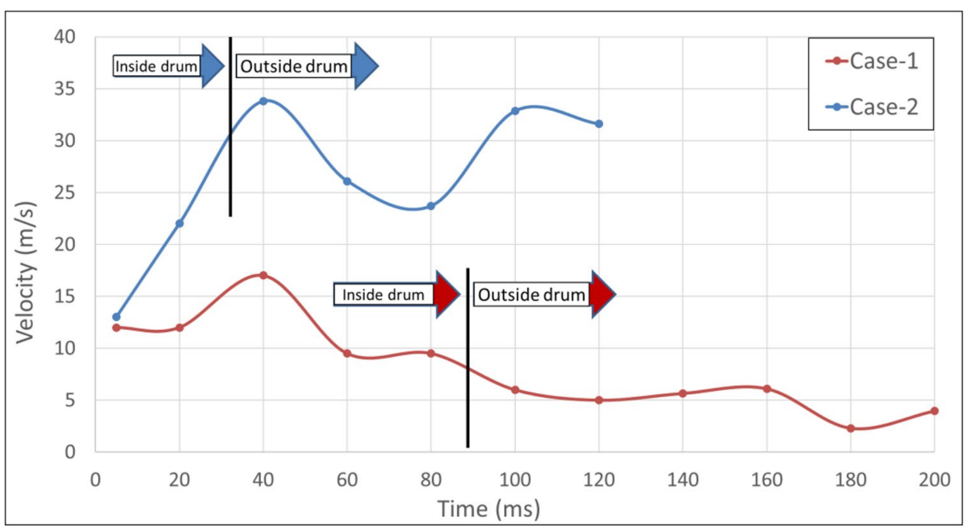


Fig. 21 Comparison of flame front propagation velocity over time based on kinetic rate of reaction

6 Conclusions and Future Work

This modeling effort successfully demonstrates the viability of integrating methane combustion model into a full-scale, 3D longwall bleeder ventilation CFD model. From these results, researchers conclude that even small ignitions can initiate major explosions underground. The pressure from an explosion can divert airflow away from the face and tailgate, creating more explosive mixtures near the face or potentially transition into coal dust explosions, as was the case in The Upper Big Branch disaster in 2010. Larger volume of explosion gas mixtures around

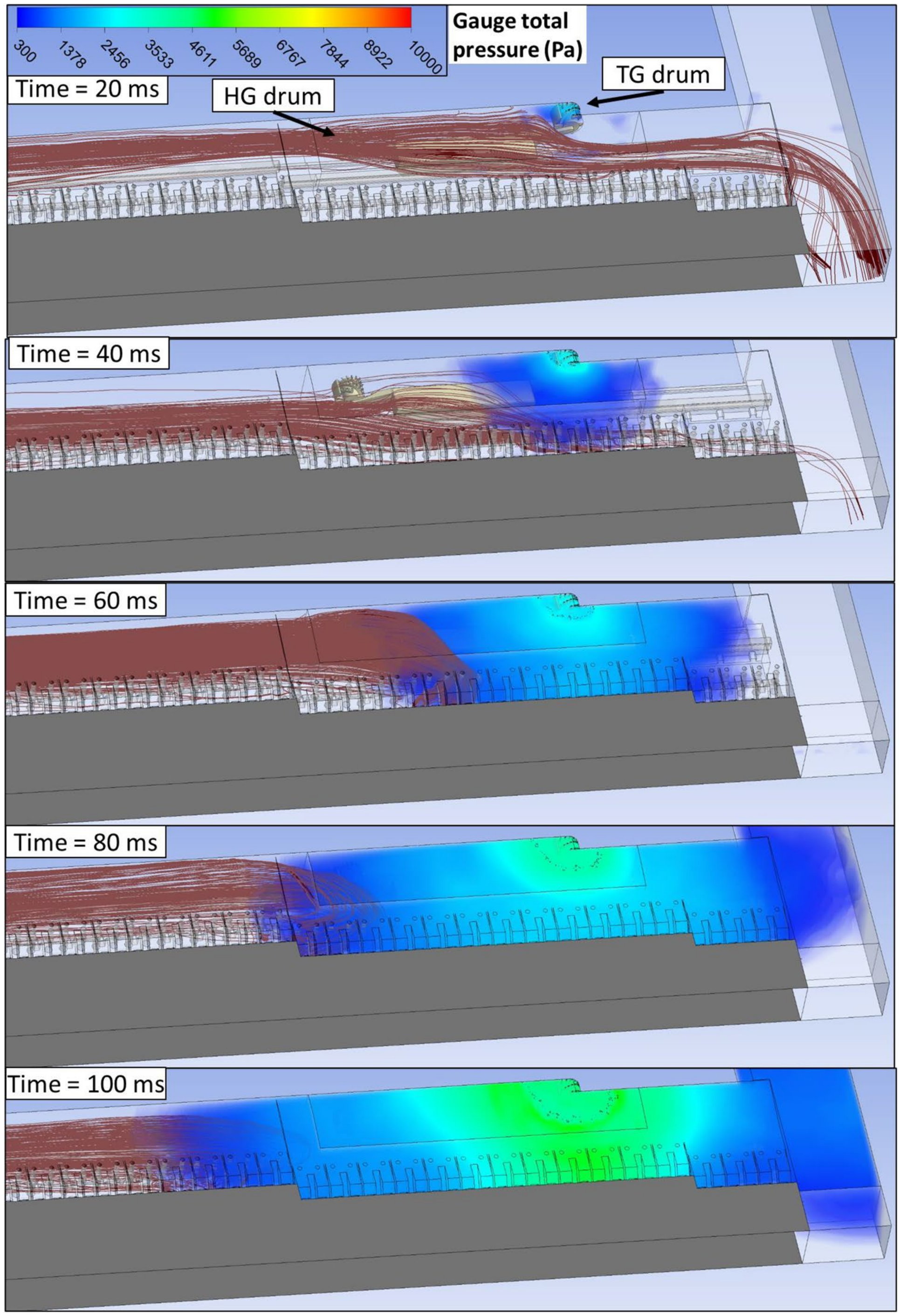


Fig. 22 Volume rendering of total gauge pressure showing ignition and explosion overpressure for case-2. Brown lines represent the streamlines of airflow in the longwall face

the ignition can significantly increase the resulting flame propagation speed and pressure generated.

3D, full-scale CFD modeling is required to better understand the fundamental physics of an underground longwall coal mine explosion and the potential impact of the explosion. This study has also demonstrated the feasibility of modeling a methane gas explosion in a longwall coal mine using commercial CFD software and has potential for future research, including:

- Expansion and impact of methane explosions for different ventilation scenarios and ignition locations
- Evaluation of explosion prevention and mitigation strategies, including explosion barriers

- Improvements in ventilation layout
- Structural design of ventilation control structures and mine seals

The CFD model utilizes a flame kernel and an ignition energy source to represent an ignition during the shearer cutting operation. The representation of frictional ignition via the ignition energy, ignition energy duration, and other ignition source shapes such as hot smears left on the roof from worn bits on the shearer drum is currently being expanded to investigate. Once validated, the model can be used to predict the potential impact of a methane explosion occurring inside the longwall face area for different ventilation scenarios.

Balancing computational time and model accuracy remains a challenge when integrating combustion model into a full-scale longwall ventilation model. Current simulations take approximately 15 days to simulate the first 200 ms of a methane–air explosion using 4×36 cores of high-performance computational power. Combination of advance modeling techniques such as partial longwall sections replacement with profile boundaries and data interpolation, adaptive meshing, and adaptive time step are required to resolve this issue. However, further studies need to be done to test the viability and limitation of these techniques.

Funding This research was funded by the National Institute for Occupational Safety and Health (NIOSH) under contract number 211–2014-60050 and Alpha Foundation under grant number AFSTI14FO69. These supports are gratefully acknowledged. This work was performed on the Colorado School of Mines MIO and Wendian High Performance Computers.

Declarations

Conflict of Interest The authors declare no competing interests.

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