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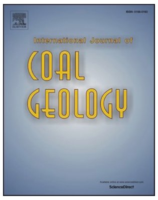

Impact of goaf gas drainage from surface vertical boreholes on goaf explosive gas zones

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ABSTRACT

Goaf gas drainage is extensively employed in Australian gassy underground coal mines to manage safety and productivity and to mitigate gas emissions. As mining operations reach greater depths and produce higher levels of gas emissions, narrower spacing between adjacent vertical goaf boreholes and higher suction pressure are increasingly being adopted. While this proactive goaf gas drainage design enhances gas extraction efficiency, there is a concern that an increased amount of ventilation air might be drawn back into the deep goaf, potentially resulting in the formation of an explosive gas zone (EGZ) composed of methane-air mixtures. Extensive goaf gas drainage data from various Australian coal mines have undergone detailed analysis in preceding back analysis studies (Wang et al., 2022a, 2023). These findings serve as crucial validation input for a CFD model of the goaf, providing ventilation engineers with visualization of an otherwise inaccessible environment. In this paper, the simulation outcomes of the CFD model were integrated with Coward's triangle to demarcate potential EGZ within the active goaf areas. It indicated that the EGZ was pushed far away from the longwall face under the impact of intensive goaf gas drainage compared to the EGZ without the active goaf boreholes, exhibiting a 'U-shaped' distribution. Furthermore, this study delves into the gas drainage factors influencing EGZs in the goaf, emphasising the impact of various gas drainage designs on gas explosion risks within the goaf. Factors such as the number of active boreholes and completion depth are assessed, with the size of EGZ serving as a quantitative evaluation criterion. Therefore, this paper plays a pivotal role in optimising goaf gas drainage efficiency, striving to minimise gas emissions into the atmosphere while upholding the priority of mining and worker safety.

1. Introduction

Longwall mining is a highly efficient and productive technique for coal extraction from underground mines. This technique involves using a shearer that moves back and forth across a panel of coal seam, while the roof behind the hydraulic support is allowed to collapse and create a porous zone called the goaf (Karacan et al., 2007a; Szurgacz and Brodny, 2020; Tutak et al., 2020). One of the major benefits of longwall mining is the impressive resource recovery rates it can achieve, far surpassing those of most other coal extraction methods and ensuring optimal utilisation of coal resources. Despite its advantages, gassy longwall coal mining carries certain risks. A significant hazard is the release of gases such as methane, carbon dioxide, and other hazardous gases liberated from the extracted coal seam and surrounding gas bearing strata. Methane, the predominant gas found in coal seams, permeates into the goaf from the surrounding strata (Tutak and Brodny, 2017; Brodny and Tutak, 2021). It may form a flammable and explosive methane-air mixture when combined with leaked ventilation air from the longwall face, particularly when the methane concentration falls within the range of 5–15% (Coward and Jones, 1952; Karacan et al., 2011). If this mixture combines with an ignition source, such as coal heating, it poses a significant risk of causing severe injuries or even fatalities among workers, in addition to causing substantial damage to infrastructure and equipment. Over the recent years, multiple mine fires and explosions have

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hinted at the presence of an Explosive Gas Zone (EGZ) in the longwall goaf (Brune, 2013). Table 1 lists some of the most significant gas explosion incidents in the major coal-producing countries since 2000 (Cheng et al., 2012; Mishra et al., 2018; Zheng et al., 2019; Zhang et al., 2022). These incidents provide substantial evidence of the existence of explosive gas mixtures within and surrounding the perimeter of the goaf. Therefore, effective management of explosive gas mixtures, particularly regarding the position and size of the EGZ, has garnered significant attention for ensuring mining safety in underground coal mines.

To control gas emissions from various sources, the industry has implemented a range of gas drainage methods, such as surface to in-seam (SIS) boreholes, underground to in-seam (UIS) boreholes, and cross-measure boreholes (Lunarzewski, 2001; Karacan et al., 2011). In addition to improving mining safety, these gas drainage methods can also reduce greenhouse gas emissions and convert captured methane into a large amount of energy (Hungerford et al., 2013; Salmachi and Karacan, 2017; Zheng et al., 2016, 2017). The emitted coal mine methane significantly contributes to atmospheric greenhouse gas levels, as methane exhibits a global warming potential 80 times greater than that of carbon dioxide over 20 years and remains 21 times more impactful over a span of 100 years (Warmuzinski, 2008; Mar et al., 2022). Goaf gas drainage using vertical boreholes as a post-drainage method has been practiced in Australian mines for nearly 40 years, and the technique has evolved significantly since its early days. The history of Australian and overseas applications of vertical boreholes, as well as borehole spacing, is captured elsewhere (Belle, 2017). Initially, the Australian implementation of goaf gas drainage was modelled on experiences from US mines and optimised using computational fluid dynamics (CFD) modelling to determine the design, placement, and spacing of boreholes (Balusu et al., 2002; Ren and Balusu, 2005, 2009). Based on these historical studies, vertical boreholes are typically drilled on the tailgate side of the longwall goaf, located 30 to 70 m from the tailgate side edge and 5 m to 10 m from the working seam. However, as mining operations become deeper and produce higher gas emissions, coal mines have adopted more aggressive goaf drainage designs featuring narrower spacing between boreholes and stronger suction pressure applied on the top of the borehole. While this approach improves the boreholes' gas capture capacity, it has the potential to change the goaf pressure distribution and exacerbate ventilation air leakage (Saki, 2016; 2017). As a result, this may elevate the risk of gas explosions within the goaf.

The Coward explosive triangle is a widely recognised tool for promptly and efficiently assessing the explosive potential of mixtures containing air and combustible gases (McPherson, 1993; Cheng et al., 2012). In 1925, the U.S. Bureau of Mines (USBM) and the British Safety in Mines Research Board initiated a joint effort to explore the flammability and explosive limits of mine gases. As part of this collaboration, British chemist H.F. Coward and American scientist G.W. Jones conducted experiments with varying concentrations of combustible gases and oxygen to determine their flammability and explosive limits (Coward and Jones, 1952). The outcome of these experiments led to the creation of Coward's triangle (Fig. 1), a graphical representation that effectively illustrates the explosive potential of various gas mixtures. Initially, the Coward's triangle experiments considered three combustible gases: methane, carbon monoxide, and hydrogen. The explosiveness of a mixture formed by these gases when interacting with air is determined by the relative proportions of the combustible gases and oxygen. As illustrated in Fig. 1, this triangle is divided into different zones: the explosive zone, non-explosive zone, one non-explosive zone (which can become explosive with more air), and another non-explosive zone (which can become explosive with more combustibles).

Table 1
Significant recent gas explosion incidents in major coal-producing countries since 2000.

Country	Mine	Year	Fatalities
China	Chenjiashan	2004	166
	Sunjiawan	2005	214
	Xinyao	2007	105
	Xinxing	2009	104
India	Bhatdee	2006	54
	Anjan Hill	2010	14
New Zealand	Pike River	2010	29
Pakistan	Sorange	2011	45
Poland	Halemba	2006	21
	KWK Wujek Ruch Slask	2009	20
Russia	Ulyanovskaya	2007	108
	Raspadskaya	2010	66
	Komi regoin	2013	18
	Listvia Shnaya	2021	52
Turkey	Karadon	2010	30
	Soma	2014	301
Ukraine	Zasyadko	2007	80
	Suhodolskaya-Vostochnaya	2011	19
US	Sago	2006	12
	Upper Big Branch	2010	29

Given that coal mine methane constitutes the primary gas component in the goaf, the distribution of methane and oxygen is regarded as a critical indicator in goaf gas explosion risk management, which have been extensively studied. Brune (2013) analysed the explosion hazard resulting from the formation of methane-air mixtures in the goaf. In particular, CFD modelling has been employed to understand the development of EGZs in the goaf using the red-coloured zone of Coward's triangle (Brune, 2013; Brune et al., 2016; Brune and Saki, 2017). This analysis revealed the presence of EGZ across the panel behind the working face under the U-type ventilation system, as illustrated in Fig. 2. Additionally, the effectiveness of nitrogen injection as a control measure was assessed. Saki et al., 2017) discussed the effect of ventilation air quantities on methane concentrations and the formation of EGZ in the goaf through a parametric study. Their findings indicated that an increase in face air led to a reduction in CH_4 concentration at the tailgate side and an increase in the size of EGZ and methane-air mixture explosion hazards. Moreover, some Chinese scholars also used the explosion triangle to analysis the gas explosion risks in the goaf (Li et al., 2020; Zhu et al., 2022). Li et al. (2020) examined the effects of ventilation air quantity and seam gas emission on the distribution of oxygen and methane concentration in the longwall goaf, providing valuable insights for enhancing safety measures in underground gassy longwall goafs. Zhu et al. (2022) used COMSOL to simulate potential hazard zones in the goaf under the influence of various combustible gas, including CH_4, CO, C_2H_6, and C_2H_4. Overall, CFD modelling serves as a crucial tool for assessing safety hazards of coal mining and improving measures to prevent gas explosions. However, their simulations only focused on individual physical processes, without considering the influence of

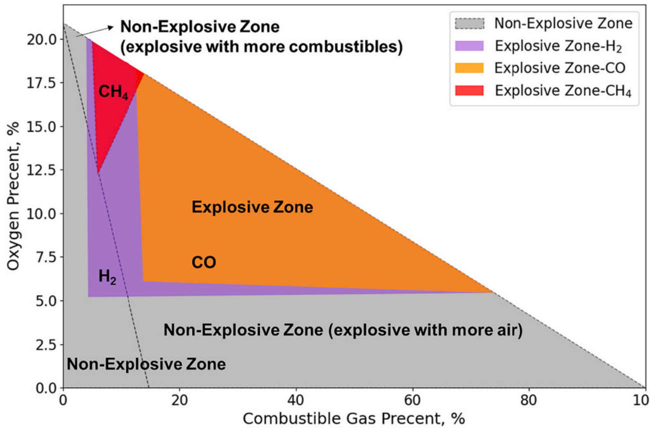


Fig. 1. The Coward explosive triangle for three combustible gases: CH_4, CO, and H_2 (modified based on Cheng (2018)).

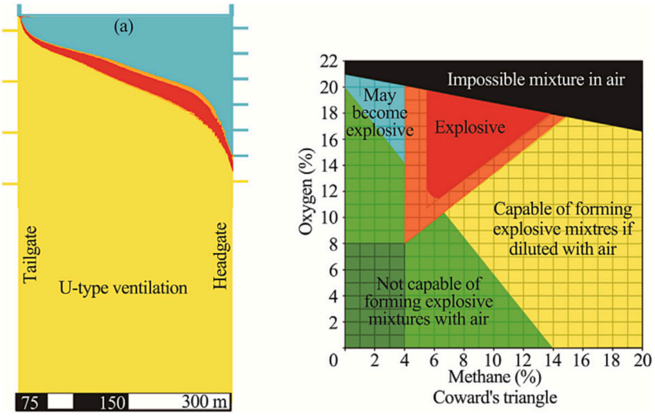


Fig. 2. The EGZ under the U-type ventilation (Brune and Saki, 2017).

intensive goaf gas drainage on the goaf atmosphere and its corresponding effects on EGZs. A serious concern has been raised in Australian highly gassy coal mines as the goaf gas drainage capacity has reached 20,000 l/s in some Queensland mines, which will significantly change the goaf atmosphere so as the shape and size of explosive gas zones, if not operated appropriately.

Furthermore, researchers have employed numerical simulation techniques to gain insights into the goaf gas atmosphere and enhance the goaf gas drainage efficiency by optimising borehole parameters. For instance, Balusu et al. (2002, 2004, 2005) developed a CFD model to depict gas flow in the goaf, aiming to formulate effective strategies for gas control and prevention of spontaneous combustion in highly gassy mines. Their findings indicated that O_2 demonstrates a higher concentration and travels a greater distance into the goaf on the maingate side compared to the tailgate side, where there was no intensive goaf gas drainage. Additionally, Ren and Edwards (2002) employed CFD models to improve the design of surface goaf holes and found that the borehole position plays a crucial role in achieving a better gas production rate. CSIRO conducted an additional CFD study, supported by the industry, to investigate goaf gas distribution in longwall panels covering distances of 1.0 km, 3.0 km and 6.0 km (Balusu et al., 2019). Their research delved into various mining parameters, proposed gas drainage strategies, and recommended increasing the injection of inert gas to effectively inertise the goaf area in longer panels. Karacan et al. (2006, 2007a, 2007b), Karacan, 2009a, 2009b) introduced a reservoir simulation model to explore the effects of borehole design and operational conditions on goaf gas drainage performance based on the U.S. mines. Moreover, other researchers (Guo et al., 2015; Qin et al., 2015; Qin et al., 2017) applied CFD modelling to simulate the goaf pressure distribution and gas flow pattern under various mining conditions, including horizontal boreholes drainage conditions, the depth of goaf different zones and gas emission characteristics. These simulation results provided valuable guidance for both evaluating the goaf environment and enhancing the performance of goaf gas drainage.

The investigations mentioned above have established a baseline for simulating methane-air explosive mixtures in the goaf. However, the composition of goaf gas mixtures and the impact of applying intensive goaf gas drainage on the goaf atmosphere during the longwall production period has not been well understood. Given that goaf drainage is widely employed as an effective tool to control gas exceedance in Australian gassy mines, an increased ventilation air leakage in the goaf is anticipated as a result of low suction pressure applied by goaf boreholes (Ren and Balusu, 2005, 2009). This raises concerns about potential gas explosion hazards and a decrease in the purity of captured gas due to excessive goaf drainage pressure or poorly managed drainage designs (Belle, 2017; Si and Belle, 2019). Additionally, the EGZ may change dynamically depending on goaf drainage performance throughout the entire production period. Consequently, the EGZ distribution in these scenarios may differ from that in previous studies conducted without the influence of goaf boreholes. Thus, achieving a delicate balance between goaf drainage efficiency and associated operational risks in goaf management requires thorough scientific exploration.

This paper aims to delineate the 3D distribution of the EGZ in the goaf, considering the influence of intensive goaf gas drainage from surface vertical boreholes. Building upon prior research by Wang et al. (2023), a CFD model was established for a case study mine featuring the wide application of goaf vertical boreholes for gas drainage purposes. The CFD model has been calibrated using goaf gas profiles derived from extensive field goaf gas drainage data collected from Australian underground longwall panels. Moreover, this paper leverages field data more effectively to analyse scientific issues, considering previous studies have not endeavoured to explore the goaf atmosphere utilising a large amount of goaf drainage production data (Si and Belle, 2019). It employs the simulation results of CH_4 and O_2 concentration simulation results obtained from the goaf CFD model along with the well-established Coward triangle to accurately locate the positions where gas explosion risks may occur in the goaf. Furthermore, this paper focuses on assessing the impact of various goaf gas drainage conditions on the size and shape of the EGZ, which is crucial for predicting potential risks and guiding engineers in adopting effective control strategies.

2. CFD modelling background

2.1. Case study mine

This study employed a broad range of goaf drainage data obtained from Mine A, an underground coal mine located in Australia. In Mine A, coal was extracted using the traditional longwall retreat mining technique. Furthermore, the operation panels have a coverage depth ranging from 250 m to 500 m and a seam thickness of 2.8 m. Si and Belle (2019) reported that the weekly production rate can reach approximately 200,000 t. The amount of gases released from Mine A coal seams range from 5 to 18 m^3/t, with the seam gas composition measured onsite being primarily methane, which constitutes over 98% of the total gas (Belle, 2017). Bedsides, Mine A used a U-type ventilation system (50 m^3/s to 60 m^3/s air flow) during its production.

Longwall A (LWA) within Mine A was chosen as the case study panel as shown in Fig. 3. The panel has a width of 350 m and a length of 3600 m. On the tailgate side of LWA, 74 vertical boreholes were placed, denoted as TG01 to TG74. In accordance with previous CSIRO research and high production operational experiences, these boreholes were spaced approximately 50 m apart (Belle, 2017) and located approximately 30 m from the tailgate side edge (Balusu et al., 2002, 2004, 2005, 2019). The completion of boreholes in LWA are similar to those described by Si and Belle (2019), with a diameter of 250 mm and a bottom situated about 10 m above the working seam. Furthermore, the boreholes began operating approximately 25 m after the longwall working face had passed by to reduce the oxygen presence in these boreholes.

In terms of gas monitoring, comprehensive strategies were implemented for each borehole at LWA, which encompassed handheld gas monitors, telemetric gas sensors, and bag sample tests. Gas samples from the wellhead of each borehole were also regularly collected and assessed multiple times a day using handheld devices. These instruments facilitated real-time monitoring of various gas concentrations, including CH_4, O_2, CO, and CO_2 throughout the entire production period. Moreover, the gas drainage system in use at Mine A was equipped with pressure transducers, enabling the determination of static and differential pressures within each borehole. Furthermore, the CFD modelling results presented in this paper were validated by comparing them with daily average measurements of gas concentration, gas flow rate, and suction pressure obtained from boreholes TG01 to TG24, as illustrated in Fig. 3 (a). In Fig. 3 (b), a stratigraphic map of the target coal seam and its adjacent strata at LWA is presented. Additionally, the primary sources of

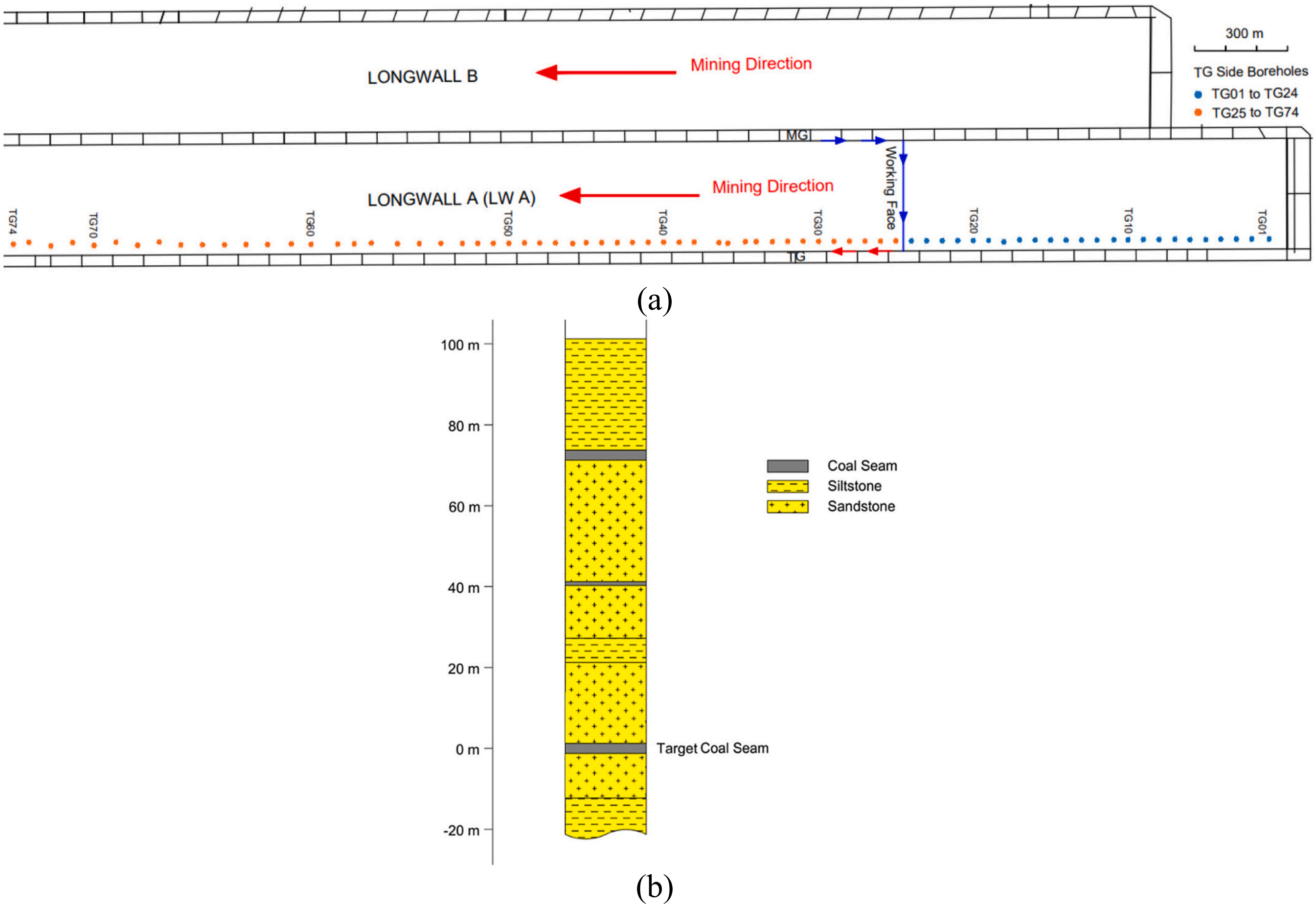
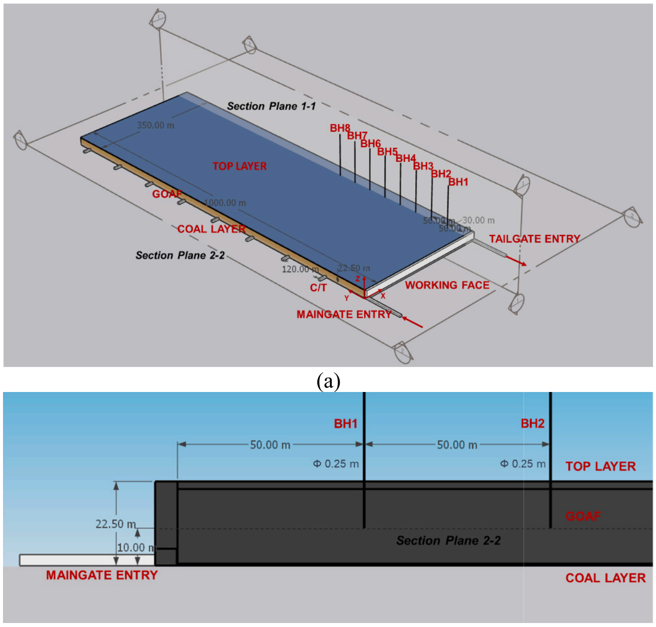


Fig. 3. (a) Schematic layout of vertical goaf boreholes and (b) stratigraphic map of the target coal seam and adjacent strata in the case study longwall panel, LWA (modified based on Wang et al. (2023)).

gas emissions in this case are from the upper strata of the target coal seam, with the nearest coal seam in the lower strata being more than 20 m away from the target seam. Thus, gas emissions from the floor pose a challenge in reaching goaf vertical boreholes. Detailed analyses of goaf gas behaviour within LWA have been extensively documented in Si et al. (2021), Xiang et al. (2021), and Wang et al. (2022a, 2022b, 2023). As a result, the findings of the field data analysis will not be repeated here.

2.2. CFD modelling background

This study employed ANSYS FLUENT, an advanced commercial CFD software, to develop a CFD model to analyse gas distribution in the longwall active goaf under the influence of multiple goaf boreholes operating simultaneously. As a result, the potential EGZs within the goaf can be simulated based on the distribution of methane and oxygen. Given the geometric conditions and the U-type ventilation system in LWA, a simplified goaf geometry model was established, as depicted in Fig. 4 (a). The width of the geometry model is 350 m, while its length has been reduced to 1000 m to only cover boreholes in the start-up stage and expedite computation time. In Fig. 4 (a), Section Plane 1–1 is situated 30 m from the tailgate side edge, representing the vertical location of the boreholes. Section plane 2–2 is positioned 10 m above the target coal seam, corresponding to the boreholes' completion depth. In the zoomed view of Section Plane 1–1 shown in Fig. 4 (b), the model has three layers with a total depth of 22.5 m: the top layer is 2 m thick, the goaf layer is 20 m, and the bottom coal layer is 0.5 m thick. The height of this goaf geometry model is determined by industry experience and generally covers the depth of the goaf caved zone. Furthermore, the maingate entry serves as the exclusive inlet for ventilation air. The leaked air



(b)

Fig. 4. The LWA goaf geometry model (a) in 3D view (b) cross section view at Section Plane 1–1.

ultimately exits from the tailgate entry after circulating around the perimeter of the active goaf. Additionally, this model incorporates eight active vertical boreholes as outlets. This gas drainage design is implemented because there are a maximum of eight boreholes to simultaneously extract gas on the same day in LWA, which can effectively manage the tailgate return gas levels. Each borehole has a diameter of 0.25 m and is labelled as BH1 to BH8 in the order of proximity to the working face. BH1 is situated 50 m from the working face, while the remaining boreholes (BH2 to BH8) are spaced 50 m apart.

Once the geometry model is established, an appropriate mesh is selected, and the entire volume is divided into multiple computational grids. In this paper, the geometry model was divided into ~12 million hexahedral elements using the cut-cell method, employing multiple sizes (0.05 m, 1.5 m, and 5 m). The final model achieved an excellent quality mesh metric, with more than 98% of elements falling within the range of 0.95 to 1 for orthogonal quality and 0 to 0.25 for skewness. These grids are then employed in FLUENT to solve for the conservation of mass, momentum, and energy using the finite volume method. Within the FLUENT solver, fluid parameters and physical properties can be configured. In the defined working face area considered as a free-flow domain in this CFD model, airflow is assumed to be entirely turbulent, utilising the Standard k-ε turbulence model and standard wall function (ANSYS, 2020). In contrast, the airflow in the goaf area is defined as laminar within the porous media domain, with permeability implemented through a User-Defined Function (UDF). Fig. 5 illustrates the goaf permeability contour at Section Plane 2–2, corresponding to the borehole completion depth. This permeability setting is based on results from the theoretical goaf resistance model obtained through back analysis results in earlier work (Wang et al., 2022a, 2022b, 2023). In this CFD model, the depth of the goaf caved zone is approximately 20 m, and it is assumed that the permeability along the *Z*-axis remains constant over this short height. Additionally, it is assumed that the permeability is symmetrically distributed along the central lines of X = 175 m and Y = 500 m. Consequently, the goaf permeability is fully compacted at ~75 m behind the face in Fig. 5, with values ranging from 1e-4 to 1e-9 m^2.

Furthermore, this model incorporates two inlets, both delineated by specific boundary conditions: one for ventilation air and the other for methane emissions. The maingate entry, serving as the exclusive source of air intake for the longwall working face, is configured as a velocity inlet. This ventilation inlet supplies fresh air to the working face at a magnitude of 60 m^3/s. Accounting for the molar fraction of the gas mixture in the atmosphere, the air leakage from the ventilation inlet consists of 20.93% O_2. Additionally, the methane source in this model is simplified as a velocity inlet across the top layer, governed by the UDF code. This simplification is employed because nearly all coal in the targeted seam has been extracted in this case. As illustrated in Fig. 6, each blue dot represents the daily CH_4 flow rate in each borehole of LWA, calculated by multiplying the field-measured total flow rate results by their corresponding CH_4 concentrations. Moreover, the blue and orange solid lines represent the median and quartile values of field gas emissions, smoothed over a 20 m rolling average along the working face direction. Thus, the fitting curve represented by the green dashed line in Fig. 6 was utilized to set the gas emission rate in this CFD model. The gas emission input increases from 600 l/s to a peak value of 1000 l/s at 100 m from the face, then decreases to around 400 l/s at 400 m from the face, after which it stabilises. Considering the gas reservoir conditions of Mine A, the gas emission purity is presumed to be 100% CH_4 to streamline the CFD modelling simulation. Within this CFD model, apart from the tailgate entry, the gas mixture in the goaf is extracted by applying a suction pressure of −6.5 kPa at the top of eight vertical boreholes. This selection is based on field data measured at LWA, indicating that the suction pressure applied in most boreholes during the operation ranged from 4 kPa to 10 kPa, with a mean value of approximately ~6.5 kPa, as illustrated in Fig. 7. Following the instructions outlined above to establish the CFD model, the FLUENT solver converges after approximately 20,000 iterations, achieving equilibrium with residuals below 1e-3.

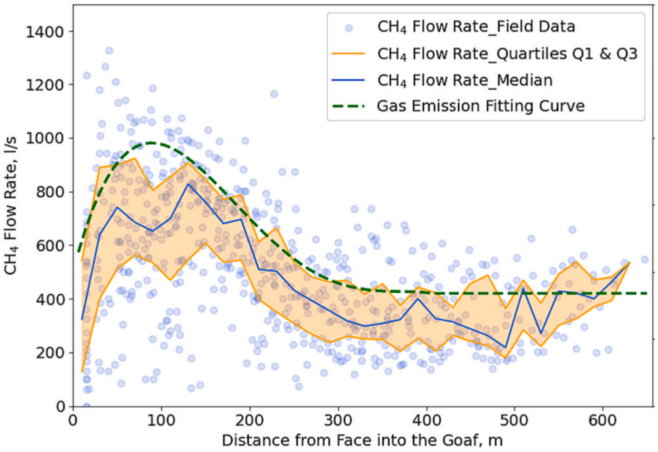


Fig. 6. Gas emission trend for methane inlet on the top layer.

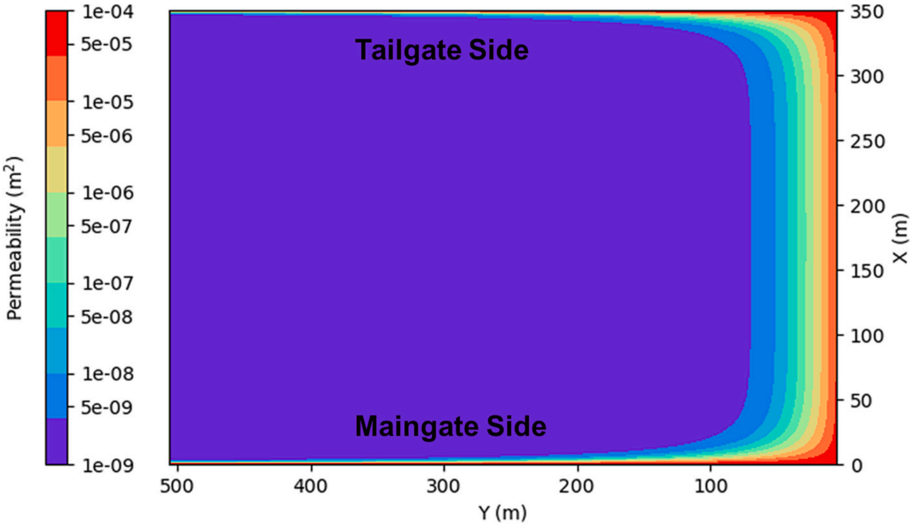


Fig. 5. Permeability distribution at Section Plane 2–2.

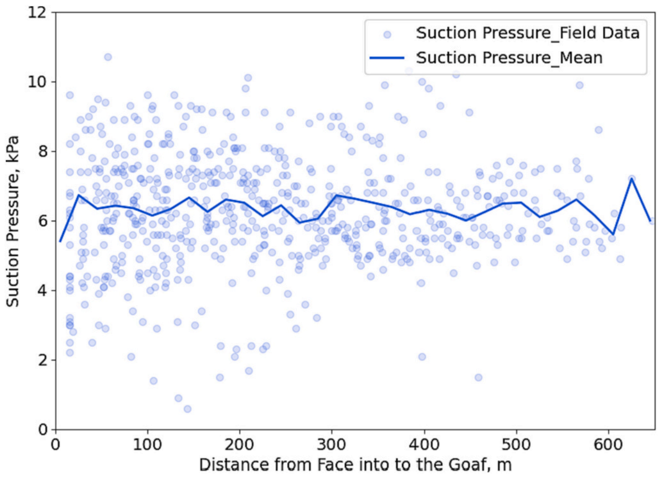


Fig. 7. Suction pressure applied on the top surface of active boreholes.

3. Modelling results

Based on the information presented in Section 2, a CFD model for the goaf has been established. This model facilitates the simulation and visualization of gas distributions within the inaccessible goaf area, under the substantial influence of intensive goaf gas drainage from vertical boreholes. Some findings derived from earlier simulations have been presented in Wang et al. (2023). In this paper, the CFD simulation results of methane and oxygen distribution are used in conjunction with Coward's triangle to pinpoint areas in the goaf that may be susceptible to gas explosions. Besides, this CFD modelling was developed without any proactive inertisation, and maingate seals are installed behind the longwall face.

3.1. Goaf gas atmosphere analysis

Fig. 8 (a) and (b) respectively depict the 3D contour views of O_2 and CH_4 distributions in the goaf. These figures incorporate several cut-planes, including Section Plane 1–1 and Section Plane 2–2 as shown in Fig. 4. In Fig. 8 (a), an O_2-rich zone (exceeding 5%) is evident behind the working face and along the tailgate side goaf, influenced by constant suction pressure applied at the top of boreholes. The zoomed-in view of the O_2 contour at Section Plane 1–1 (top right corner of Fig. 8 (a)) indicates that O_2 has been pulled up to the drainage level at 10 m above the seam, revealing a high O_2 concentration over 16%. To further inspect the O_2 ingress zone on the tailgate side goaf at various elevations, it becomes apparent that the region containing high-purity O_2 diminishes as moving higher into the goaf. This is because the top layer serves as the gas emission source in this model, with gas consisting of 100% purity CH_4 continuously penetrating into the goaf.

In contrast, the CH_4 concentration in proximity to both the working face and the tailgate side goaf registers a notable decrease. This decrease can be attributed to the sweeping effect generated by the ventilation air emanating from the working face, as depicted in Fig. 8 (b). With continuous gas emission from the top layer, the CH_4 concentration within the goaf varies at different depths, gradually increasing with goaf height. Meanwhile, the ventilation air dilutes the gas as it moves away from the roof, resulting in a low CH_4 zone (below 20%) in the lower goaf, which extends into the deeper regions of the goaf. As a result, the diluted gas, consisting of varying components at different depths, flows through the slotted casing and into vertical boreholes situated at various locations.

The accuracy of the modelling can be verified by comparing gas concentrations extracted from eight boreholes in this CFD model with the gas drainage data obtained from the LWA tailgate side boreholes. In Fig. 9, concentrations of O_2 and CH_4 extracted from field production data are presented. Fig. 9 (a) illustrates daily O_2 concentrations measured at various boreholes located at different distances from the working face, represented by red dots. Simultaneously, Fig. 9 (b) depicts CH_4 concentrations using blue dots. Additionally, the O_2 concentration in eight drained boreholes from the CFD simulation results is indicated as blue triangles in Fig. 9 (a). These concentrations decrease from ~12% in BH1 to ~3% in BH8 as one moves into the deep goaf. The O_2 content in these eight boreholes in the CFD model aligns consistently in terms of magnitude and trend with the field data. However, the O_2 concentrations exhibit significant fluctuations within 200 m close to the face, with some field data points indicating very low O_2 levels (less than 5%) or high O_2 levels (more than 12%). Apart from the potential for field measurement errors, these variations may be influenced by complex factors related to the natural characteristics of the goaf, including the goaf permeability distribution and gas emission rate. Further detailed analysis and explanation have been provided in Wang et al. (2023). Furthermore, the simulated CH_4 purity found in eight drained boreholes is represented as yellow triangles in Fig. 9 (b). As the competing gas, the CH_4 concentration obtained from the CFD modelling increases from 40% to 80%, which is consistent with the rebounding trend observed in the field data. However, CH_4 levels in boreholes situated farther away from the face exhibit a rapid increase, and the CH_4 concentrations in drained boreholes from the CFD model are higher than those indicated by field drainage data. This discrepancy arises because the gas emissions set in this model were based on continuous velocity input, while the operational gas emission zone in the field may have a limited desorption capacity. Moreover, the CFD model did not consider the coal oxidation effect. The target coal seam in this case is almost entirely mined, and the CO content of the oxidation reaction product monitored in the borehole, which is also an important gas indicator, is less than 100 ppm according to on-site monitoring (Si and Belle, 2019). Therefore, the impact of the coal oxidation reaction on the goaf atmosphere is ignored in the industrial-scale model presented in this paper. However, progressive coal oxidation would lead to the consumption of O_2, resulting in an increased inflow of leaked air into the deep goaf, thereby diluting the CH_4 concentration in reality.

3.2. Goaf explosive zone assessment

Based on Coward's triangle, the assessment of gas explosion risk depends on the O_2 and CH_4 concentrations in the goaf. Referring to the combustible and air mixture illustrated in Fig. 1, in the subsequent section, the goaf is categorised into four zones: (1) the red zone, representing an explosive mix of methane and air; (2) the green zone, indicating a non-explosive mixture; (3) the yellow zone, representing a fuel-rich mixture that becomes explosive when oxygen is added; and (4) the cyan zone, signifying a fuel-lean mixture that could become explosive when additional methane is introduced. Combining this definition with the simulation results in Section 3.1, the O_2 and CH_4 concentrations at the centre of each cell in this CFD model serve as indicators for assessing gas explosion risk in the goaf. Subsequently, each cell is colour-filled based on the Coward triangle through the UDF code.

Fig. 10 illustrates potential gas explosion risks at various horizontal and vertical cut-planes for the CFD validation conditions. Starting with the explosive zone at the coal seam level, it becomes evident that the O_2-rich area following the working face is a non-explosive zone. As the depth above the seam increases from 0 m to 20 m in the goaf, the non-explosive zone (green zone in Fig. 10) gradually diminishes. As the distance from the face increases and extends into the deep goaf, the O_2 content decreases while the CH_4 content increases. Consequently, the fuel-lean zone, represented by the cyan colour, closely follows the non-explosive zone, signifying an escalating potential risk of gas explosions with the additional gas. The EGZ at the coal seam level is effectively pulled away from the working face due to the influence of tailgate side operating vertical boreholes, and its distribution differs from the EGZ near the working face in the goaf where no drilling is performed (Fig. 2).

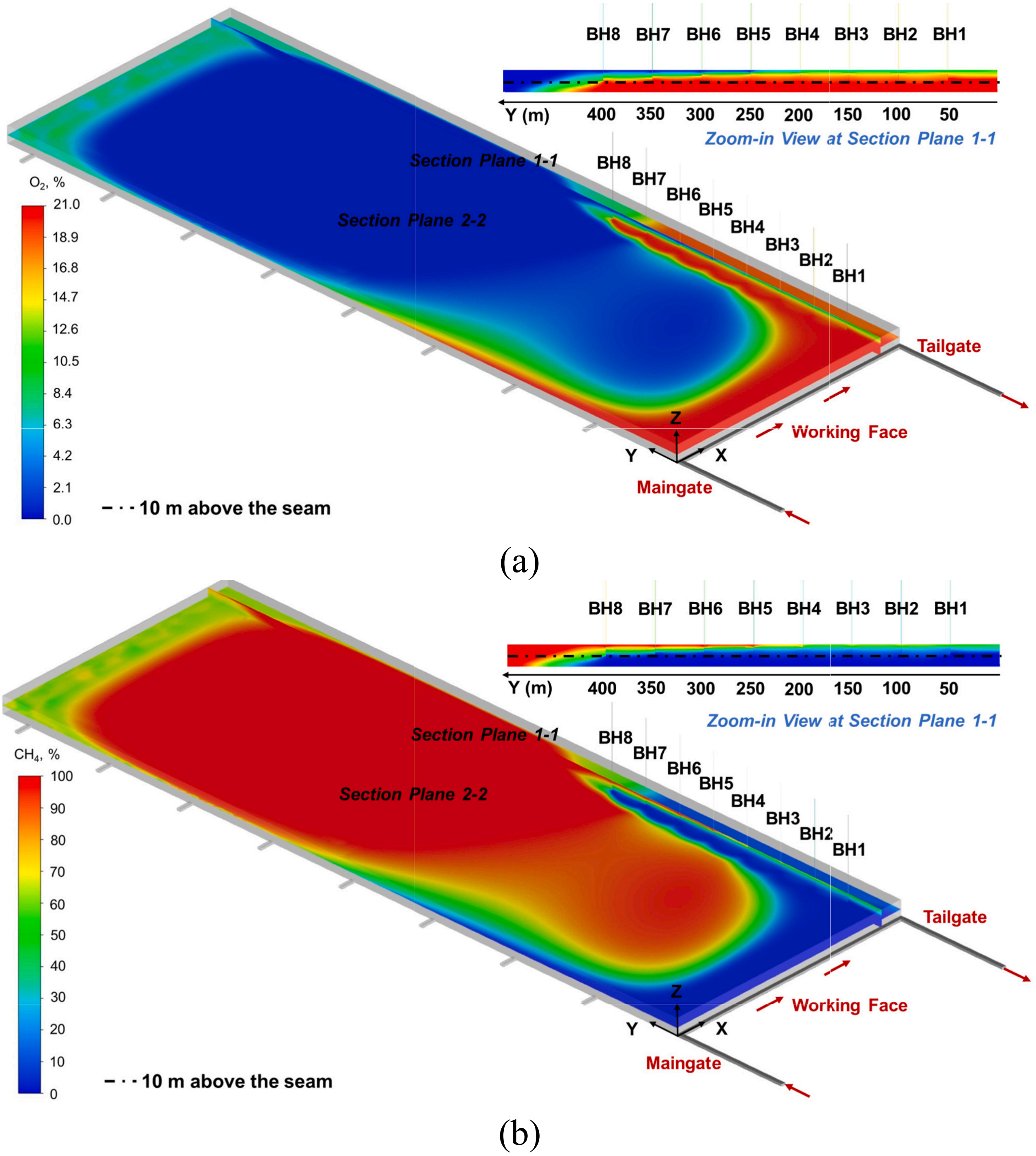
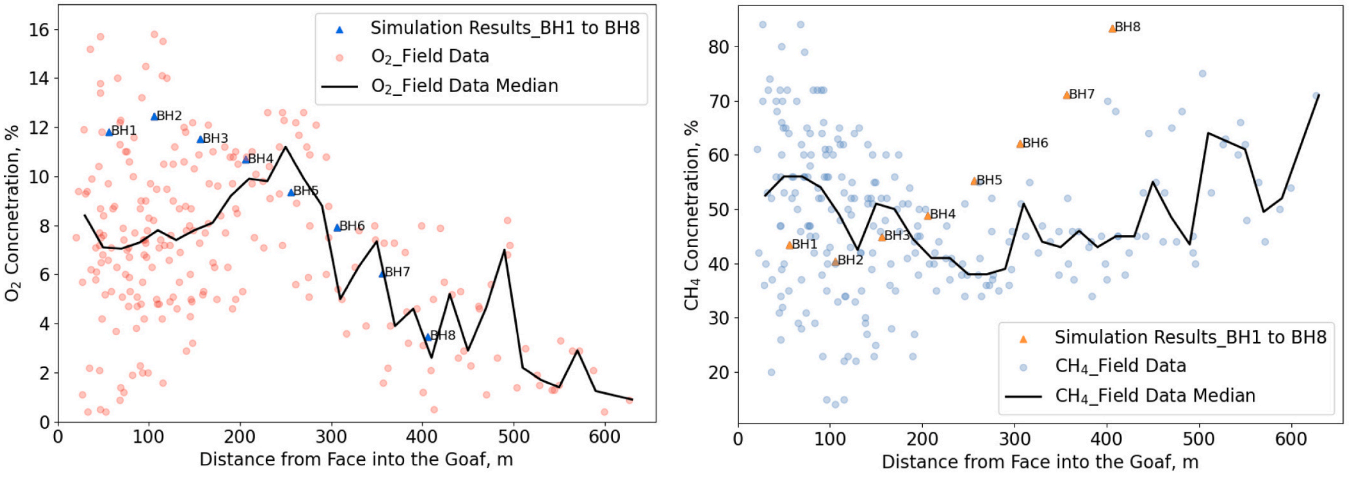


Fig. 8. (a) O_2 and (b) CH_4 concentrations: 3D gas distribution in the goaf.

This phenomenon is also discussed in Section 4.1 below and illustrated in Fig. *13* (a). In the absence of borehole drainage, the EGZ in the goaf is far from the working face on the maingate side, while it is close to the working face on the tailgate side, posing a potential safety threat to workers.

Moreover, as depicted by contours on vertical cut-planes in Fig. *10*, the EGZ rapidly recedes with increased distance from the coal seam level on the maingate side goaf. Conversely, on the tailgate side goaf (i.e., Section Plane 1–1), the EGZ accumulates at approximately the borehole completion depth. This accumulation is attributed to the application of suction pressure on top of the boreholes, causing the O_2 from the working face to be drawn upward into the higher goaf and subsequently extracted by these vertical boreholes. This phenomenon is also notably observed in the horizontal cut-plane located 10 m above the coal seam (i.e., Section Plane 2–2). Additionally, the concentration of CH_4 on the tailgate side goaf increases as it approaches the methane source from the top layer in this CFD model. Consequently, these areas are characterised as fuel-rich zone with higher gas concentrations. As the distance to the face increases, the leaked air cannot reach the deeper goaf, which also exhibits characteristics of a fuel-rich zone.

Furthermore, simulation results of drained gas composition from goaf boreholes can be utilized for comparison with field goaf gas production data, as illustrated in Fig. 11. This figure illustrates the gas content within drained boreholes, represented by black triangles for CFD



(a) (b)

Fig. 9. (a) O_2 and (b) CH_4 concentrations: CFD modelling results versus field goaf gas drainage data in LWA.

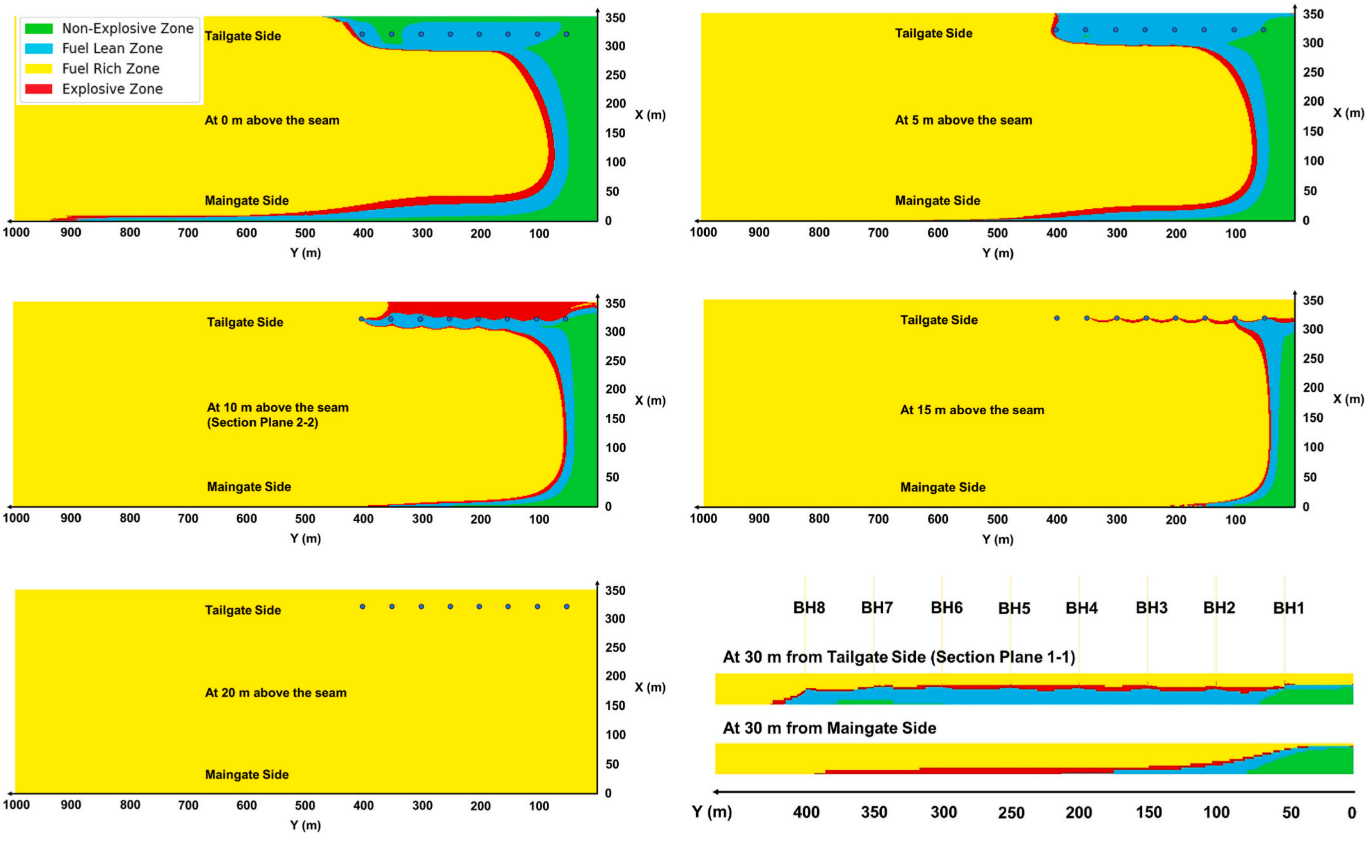


Fig. 10. Gas explosion zones at various horizontal and vertical cut-planes in the goaf.

modelling results and blue dots for field measurements. All simulation results and field data points fall within the fuel-rich zone. The reason for these triangles BH1 to BH8 lie on the boundary line is that this CFD model does not consider coal oxidation and the impact of the formation of oxidation products on the goaf atmosphere. Under the influence of coal oxidation, O_2 in the goaf will be consumed, leading to an increase in leaked air entering the deep goaf. This scenario may enlarge the size of the EGZ and elevate the risk of a gas explosion. However, as previously mentioned, since the CO content in coal oxidation products is less than 100 ppm, this paper disregards the impact of consumed O_2 content on the results. Moreover, boreholes situated farther from the working face exhibit a reduced potential for gas explosions, as evidenced by BH8 having the greatest distance from the explosive zone in Fig. 11. Conversely, boreholes in proximity to the face present a heightened likelihood of being close to the explosion zone due to higher O_2 content and lower CH_4 content. This finding is further supported by field production data, specifically the data collected closest to the red zone, which comes from monitoring results at TG01 in LWA. However, the field production data only provides insights into gas content at the top of boreholes. Thus, CFD modelling proves invaluable for assessing gas

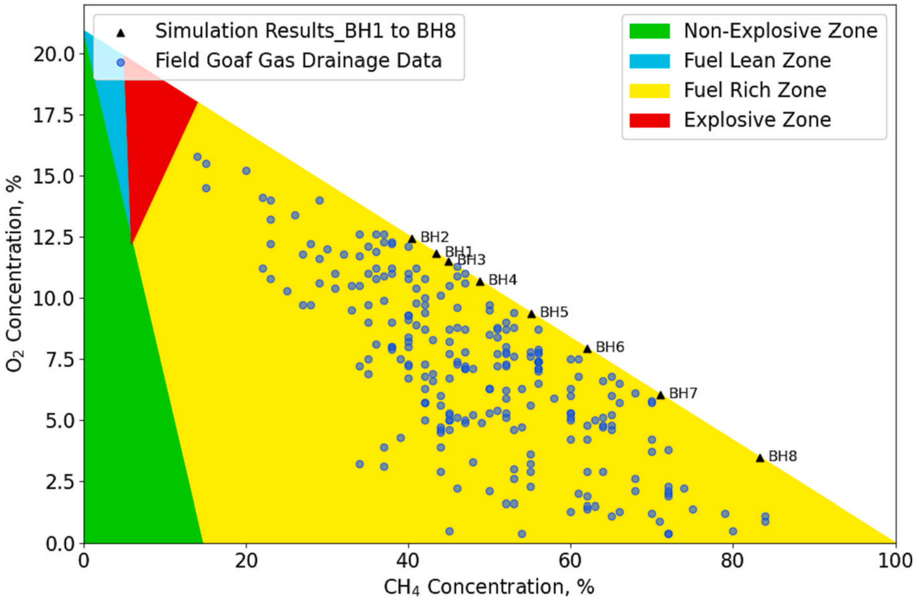


Fig. 11. Gas concentration in drained boreholes in Coward's triangle: CFD modelling simulation results versus field goaf gas drainage data.

explosion risks within the inaccessible goaf area.

To gain a more comprehensive understanding of the spatial distribution of EGZ, the 3D shape of EGZ in goaf is displayed in Fig. 12. In this specific CFD model, the EGZ exhibits a concentrated 'U-shaped' distribution behind the working face. However, it is important to note that the EGZ does not exhibit uniform distribution along the goaf's *Z*-axis, as depicted in the zoom-in cross-sectional view at the top right corner of Fig. 12. At the coal seam level, the EGZ is drawn back as far away from the working face, which is distributed further than ~80 m from the face. As the depth increases to a higher level, the EGZ expands inclining towards the upper section of the working face. Notably, the tailgate side exhibits a greater presence of EGZ compared to the maingate side at upper goaf, as a result of goaf gas drainage operations. This observation contrasts with results obtained in the absence of goaf gas drainage effect, and the impact of operating goaf boreholes will be explored in detail in Section 4. Furthermore, the size of the EGZ within the goaf can be accurately calculated using FLUENT volume integrals. This quantitative approach proves valuable in assessing gas explosion risks in various goaf scenarios in the following Section 4.

4. Discussion

4.1. Influence of active borehole numbers

Throughout the entire duration of goaf gas drainage operations, various scenarios involving different active boreholes have been observed. The simulation results of the scenario with the maximum number of operating boreholes, which is eight in this case, has been comprehensively examined in Section 3. Within this section, the impact of varying numbers of active boreholes on the effect of EGZ is quantified. Specifically, simulations are conducted with 0 boreholes, 2 boreholes (BH1 and BH2), 4 boreholes (BH1 to BH4), and 6 boreholes (BH1 to BH6), as previously outlined in Section 2, with these boreholes spaced 50 m apart from each other.

Fig. 13 illustrates the gas explosion zones at the target seam in the goaf under different active boreholes based on Coward's triangle. In the absence of gas drainage from vertical goaf boreholes, the non-explosive zone immediately adjacent to the working face (right side of Fig. 13 (a)) is characterised by significantly high O_2 content and low CH_4 content. As the distance from the working face increases, the O_2 concentration

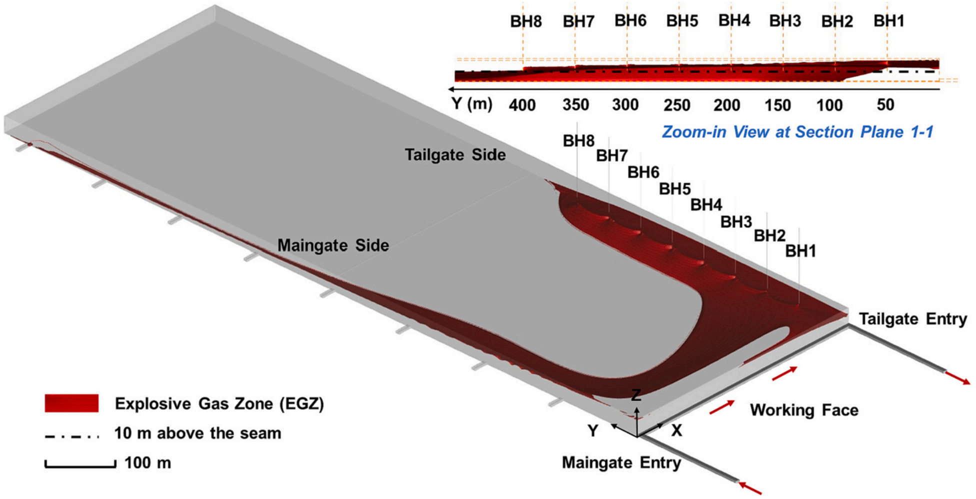
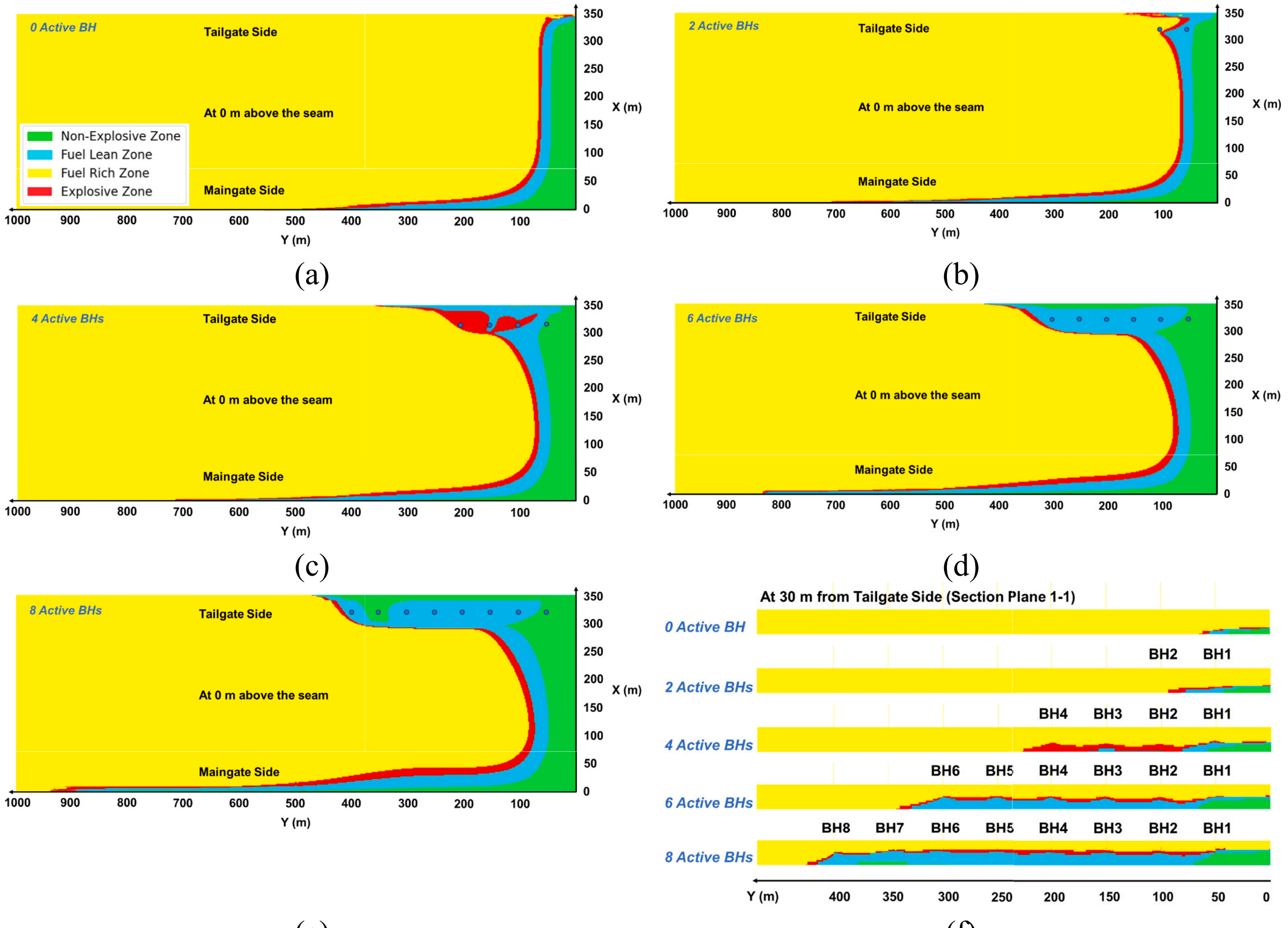


Fig. 12. EGZ 3D distribution in the goaf.



(a) (b) (c) (d) (e) (f)

Fig. 13. Shape of EGZ at the target seam level under various numbers of active boreholes: (a) 0 active borehole; (b) 2 active boreholes; (c) 4 active boreholes; (d) 6 active boreholes; (e) 8 active boreholes; and (f) cross-sectional view at Section Plane 1–1.

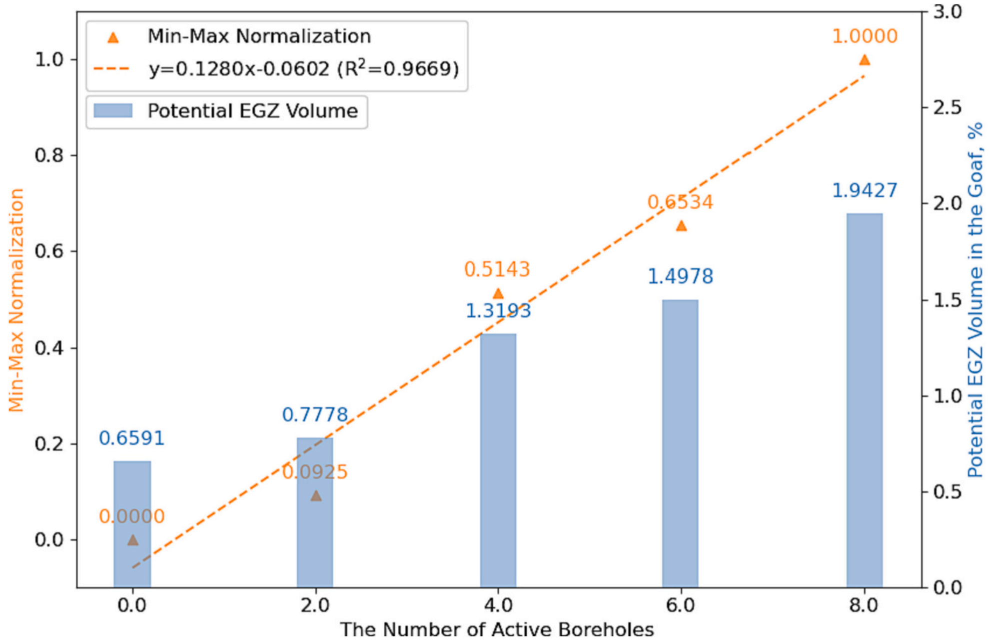


Fig. 14. The min-max normalization and the potential EGZ volume percentage in the goaf under various numbers of active boreholes.

gradually decreases. Following a brief region known as the fuel lean zone in cyan, the region transitions into the red-coloured explosive zone, which is consistent with the EGZ in Fig. 2 (Brune and Saki, 2017). Furthermore, increasing the number of operational boreholes gradually draws the EGZ into the deeper goaf and farther away from the working face, encompassing both the goaf tailgate side and maingate side. In Fig. 13 (f), the explosive zone at Section Plane 1–1 in the vertical direction under the influence of different active boreholes is compared. It is clear that simultaneous extraction from multiple boreholes, especially in scenarios involving 6 or 8 active boreholes, concentrates the EGZ near the completion depth of these boreholes. Consequently, a higher number of active boreholes increases O_2 migration into the deep goaf with a larger EGZ and elevated gas explosion risks. On the other hand, the EGZ is drawn further away from the working face (and mine operators), which may somewhat reduce ignition risk and damage should an explosion occur.

To assess the influence of multiple active boreholes on goaf explosion risks, the size of the EGZ served as an indicator. Fig. 14 presents the blue bar graph illustrating the potential EGZ volume within the goaf as a percentage of the total goaf volume. For instance, the value of 1.943% shown in Fig. 14 for the case with eight active boreholes was calculated by dividing its corresponding EGZ volume (135,987.61 m^3) by the total goaf volume (7,000,000 m^3) and then multiplying by 100%. The quantification of gas explosion risks reveals a positive correlation between the number of active boreholes and the EGZ size. Moreover, the min-max normalization was applied to scale the EGZ size under different scenarios to a specific range, ranging between 0 and 1. The orange triangles in Fig. 14, calculated based on Eq. (1), depict the min-max normalised values for scenarios with 0, 2, 4, 6, and 8 active boreholes, respectively. Additionally, an orange dashed trend line was introduced to enhance the understanding of the relationship between the number of active boreholes and gas explosion risks in the goaf. Therefore, employing a methodology that integrates min-max normalization and the EGZ percentage provides valuable insights into both the direction and magnitude of correlations. This method not only facilitates the understanding of the relative scales of features related to EGZ size but also serves as a predictive tool for estimating EGZs under various goal gas drainage scenarios based on observed trends.

$$Min - Max \text{ Normalization} = \frac{\text{X} - Min(\text{X})}{Max(\text{X}) - Min(\text{X})} \tag{1}$$

where X is the original value of the feature; Min(X) is the minimum value of the feature in the dataset; Max(X) is the maximum value of the feature in the dataset.

4.2. Influence of borehole completion depths

The goaf gas drainage method involves drilling a series of vertical boreholes from the surface to a specific depth above the working seam, typically ranging from 5 m to 10 m. Previous studies have emphasized the impact of borehole location on drainage efficiency but have

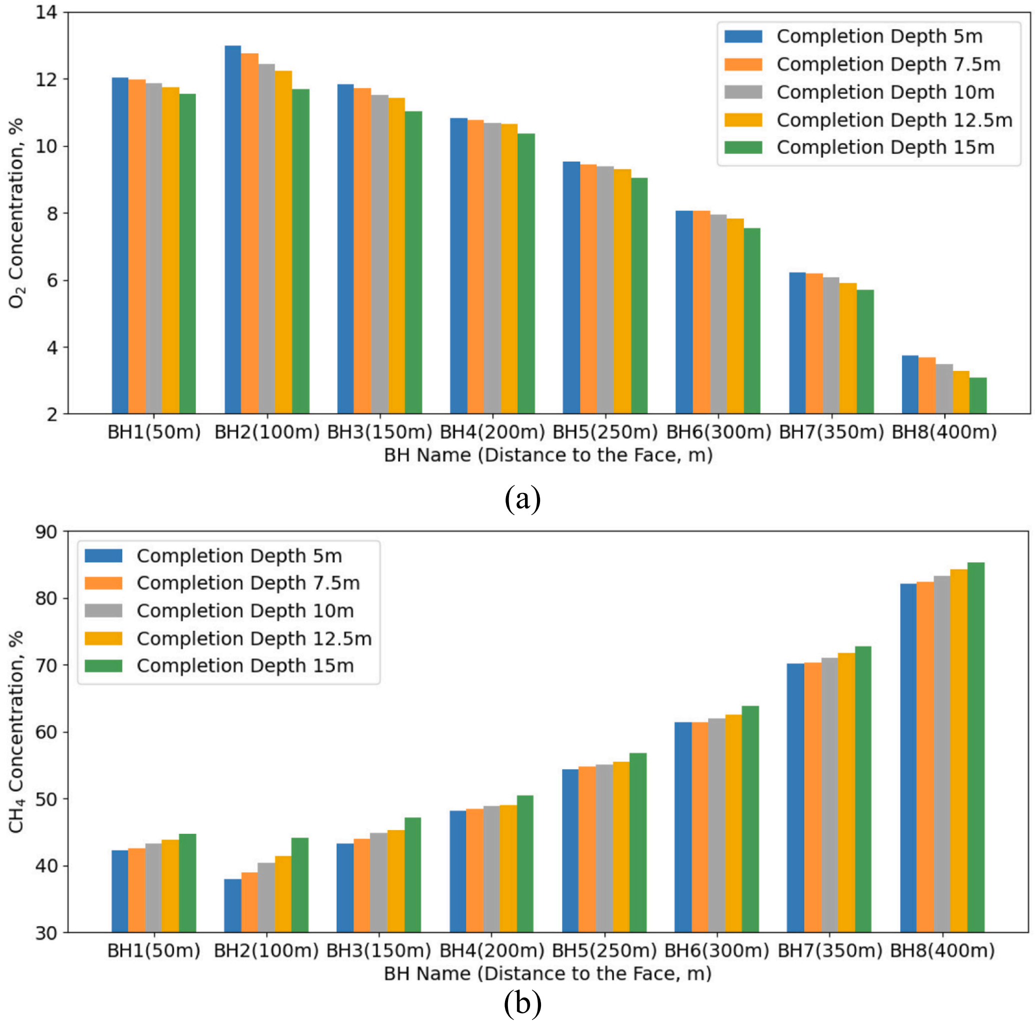


Fig. 15. O_2 and CH_4 concentration in drained boreholes under various completion depths.

primarily focused on horizontal planes at the same depths. However, the impact of vertical borehole completion depths on the goaf atmosphere and the associated potential risk of gas explosions has not been well understood. In this CFD model, the bottoms of eight vertical boreholes (BH1-BH8) are positioned 10 m above the seam in the original case. This section aims to examine the impact of different borehole completion depths on EGZs in the goaf by simulating CFD models with eight active boreholes completed at different depths, specifically at 5 m, 7.5 m, 12.5 m, and 15 m above the seam. All other input parameters and modelling setups remain consistent with those described in the previous section for the 10 m scenario.

Fig. 15 depicts the concentrations of O_2 and CH_4 in drained boreholes at varying completion depths. It is evident that under different completion depth scenarios, as the borehole moves away from the working face, the O_2 concentration exhibits a downward trend, while the CH_4 concentration shows an upward trend. Furthermore, boreholes at different locations can extract more O_2 from the face when the completion depth of vertical boreholes is closer to the target seam. Conversely, higher CH_4 content is observed in drained boreholes when the completion depth is closer to the gas source at the top layer. Moreover, the changes in O_2 and CH_4 concentrations are relatively uniform and become more pronounced when the completion depth reached 15 m above the seam. As a result, analysing the simulated O_2 and CH_4 concentrations in the goaf, in conjunction with Coward's triangle, enables the evaluation of gas explosion risks at different completion depths.

Fig. 16 displays the O_2 contour and EGZs at Section Plane 1–1 under various borehole completion depths (at 5 m, 7.5 m, 10 m, 12.5 m, and 15 m above the working seam). Based on the reference benchmark at 10 m above the seam, represented by the black dashed line, Fig. 16 (a) illustrates that the O_2-rich zone extends to higher positions when the borehole bottom is situated farther above the seam. As a result, there is a larger EGZ located at a higher position, as indicated by the red colour in Fig. 16 (b). When the borehole completion depth is closer to the target seam, a higher O2 concentration is observed at the top of boreholes, which may increase the potential for gas explosion risks in the goaf. To accurately assess the impact of borehole completion depth on the EGZ in

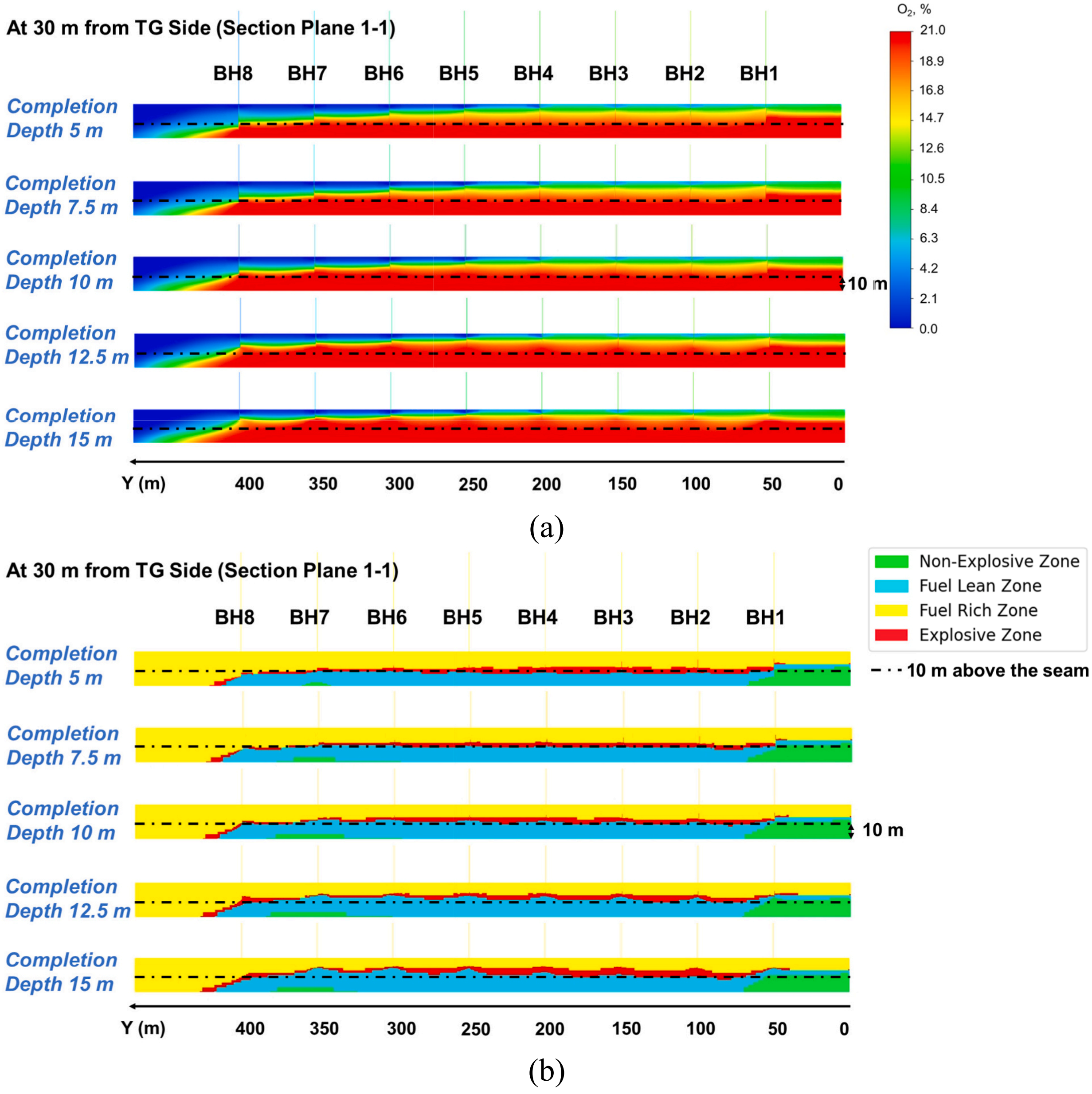


Fig. 16. (a) The O_2 contour and (b) Gas explosion zones at Section Plane 1–1 vertical plane view under various completion depths.

the goaf, Fig. 17 depicts the min-max normalization and the EGZ percentage under different completion depths. The calculation method is the same as in Section 4.1, derived from the EGZ size under various scenarios. This figure illustrates a nonlinear, parabolic relationship between the borehole completion depth and the EGZ size in the goaf, described by a quadratic fitting equation. However, the influence of this feature on the EGZ volume percentage within the goaf appears to be insignificant, consistently hovering around 2% across different borehole completion depths. Compared to the number of active boreholes, the depth of borehole completion has a lesser impact on the size of the EGZ. This observation can be leveraged for future parameter studies aimed at optimising borehole design, improving drainage efficiency, and ensuring that the risk of gas explosions and increased air leakage resulting from intensive goaf gas drainage remains within a controllable range. Therefore, this paper provides guidance for engineers to strike a balance between drainage efficiency and mine safety. For instance, boreholes drilled in areas close to the gas emission source bed are likely to achieve higher capture efficiency with minimal impact on EGZ expansion.

5. Conclusions

In conclusion, understanding the impact of gas drainage on the underground goaf atmosphere is crucial for ensuring mining safety and productivity. This study relied on back analysis results and CFD modelling to visualise the inaccessible goaf atmosphere influenced by intensive vertical boreholes. By combining the Coward's triangle with simulation results, specific areas at risk of gas explosions in the goaf were pinpointed. As shown in Fig. 12, EGZs demonstrate a distinct 'U-shaped' distribution away from the working face. Moreover, it is evident that increasing the number of boreholes not only enlarges the EGZ size but also draws them deeper into the goaf. Furthermore, when the completion depth of boreholes is close to the target seam, these boreholes can extract more O2, resulting in larger EGZs in the goaf. On the other hand, when the bottom of boreholes is far away from the seam, the O_2-rich zone and EGZ in this scenario tend to be higher up, although their size does not change much within a certain depth range. These findings are valuable for miners and engineers to make informed decisions, particularly in balancing enhanced gas drainage efficiency with potential risks arising from increased ventilation air leakage.

This study relies on extensive field goaf gas drainage data to calibrate CFD modelling. It underscores the significance of integrating real-time goaf gas monitoring systems for effective risk management. This integration enables the prompt implementation of responsive measures to mitigate potential risks before escalation. However, the CFD model built in this paper only simulates under specific mining conditions, permeability distributions, and changes in gas emission profiles, and the EGZ may vary for different underground mining scenarios and goaf drainage designs. Moreover, this paper does not consider the impact of coal oxidation, which could lead to increased temperatures in specific locations in the goaf, potentially resulting in spontaneous combustion in severe cases. This phenomenon may interact with gas explosions, posing greater hazards to mine safety. Therefore, strategies such as injecting inert gases like N_2 have been proposed to reduce the likelihood of explosive gas mixtures forming in the goaf. Integrating these methods with simulation results from CFD modelling in future research could provide a deeper understanding of potential risks in the goaf and the effectiveness of methods to control these risks, thereby improving operational safety. Consequently, enhancing borehole productivity becomes feasible while ensuring mine safety and significantly reducing the impact of greenhouse gases caused by gas emissions.

CRediT authorship contribution statement

Yuehan Wang: Writing – original draft, Software, Investigation, Formal analysis, Data curation, Conceptualization. **Guangyao Si:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Bharath Belle:** Writing – review & editing, Supervision, Resources, Data curation. **David Webb:** Writing – review & editing, Supervision, Resources, Data curation. **Liang Zhao:** Funding acquisition, Resources, Supervision, Writing – review & editing. **Joung Oh:** Writing – review & editing, Supervision, Resources, Methodology.

Declaration of competing interest

The authors whose names are listed in this manuscript certify that they have NO affiliations with or involvement in any organization or entity with any financial interest (such as honoraria; educational grants; participation in speakers' bureaus; membership, employment, consultancies, stock ownership, or other equity interest; and expert testimony

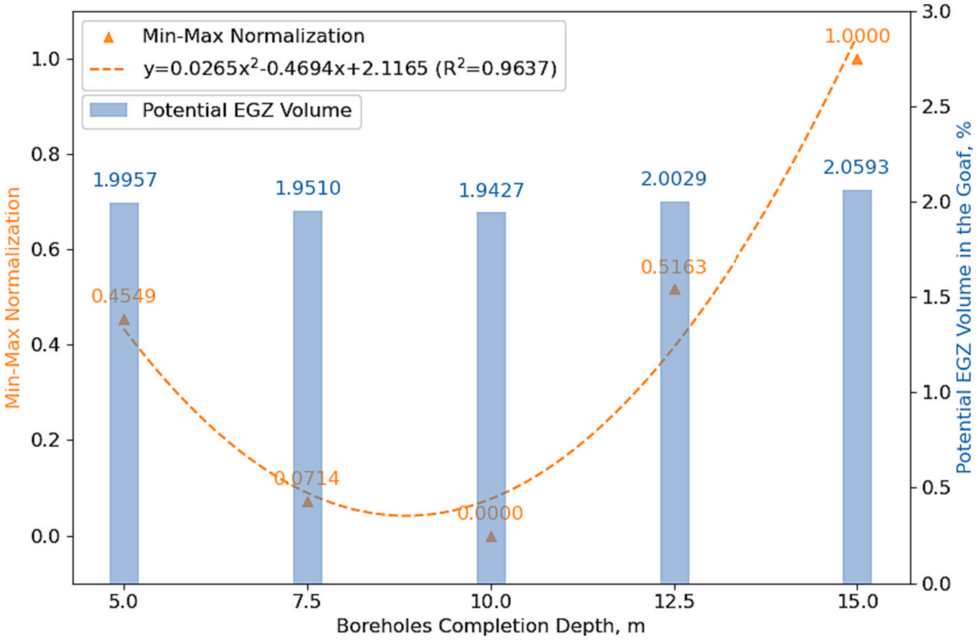


Fig. 17. The min-max normalization and the potential EGZ volume percentage in the goaf under various completion depths.

or patent-licensing arrangements), or non-financial interest (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or materials discussed in this manuscript.

Data availability

Data will be made available on request.

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