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Keywords

numerical modeling; borehole patterns; Comsol Multiphysics; CFD simulation; coal gas drainage

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A proper borehole pattern design for coal seam methane drainage in Tabas coal mine using Comsol Multiphysics

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Abstract

Optimizing the operational parameters of the borehole pattern in the coal seam includes the maximum amount of gas to be drained with the least amount of drilling, investment, and drainage time. The main purpose of this research is to properly design the drainage borehole pattern in the C1 coal seam of the Tabas coal mine. In this research, the Comsol Multiphysics software was used for numerical modeling of the boreholes. According to the method of diffusion of methane gas in a coal seam, the reduction of methane gas concentration and the amount of gas released from the coal blocks were approximated. For the gas drainage boreholes, the three patterns of the rectangular, parallelogram, and triangular forms were considered. Also, the boreholes were modeled with the three diameters of 76, 86, and 96 mm. This modeling was performed for 180 days of drainage operation and showed that the triangular pattern was more suitable than the other two patterns. The presented model is applicable in coal mines where gas drainage operations are necessary and helps engineers design the patterns of drainage boreholes to maximize their gas drainage efficiency.

Keywords: numerical modeling, borehole patterns, COMSOL Multiphysics, CFD simulation, coal gas drainage

1. Introduction

Coal is considered one of the most important sources of primary energy production in the last two centuries, and there has been a lot of planning on coal for future energy supply. Due to the increasing demand for coal extraction, deep coal mining has received much attention. These resources naturally contain more methane, and as a result, mining companies are increasingly feeling the need to make safer conditions. In addition, environmental protection laws have become much more complicated than before. Therefore, this causes mining companies spend high additional costs to ventilate this gas from the mine and release it into the atmosphere. Due to the high volume of gas released in some coal seams, mine ventilation alone cannot create a safe environment for coal mining, so degasification is necessary. Degasification transfers and extracts gas from coal seams and the surrounding rocks through vertical, horizontal, and directional boreholes.

When a methane drainage borehole is drilled in a coal seam or surrounding rocks, a low-pressure space is created, and gas is released from the trapped or adsorbed space and moves towards the borehole [1]. Degasification operations can be performed as pre-mining and post-mining drainage systems. Pre-mining drainage methods involve removing methane before the mining activity on a virgin coal seam. The objective of post-mining drainage is to increase the amount of gas removal from the coal seam and surrounding rocks and minimize the gas flow into the mine airways. Optimization of drainage boreholes is a critical issue that should be considered in the coal degasification operation. Borehole optimization significantly affects the drainage of methane gas from a coal seam and its surrounding rocks. Important borehole parameters in this optimization scheme

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include the number and diameter of boreholes, their spacing, drilling angle concerning the horizon, working face, and borehole location.

Optimization of these parameters reduces the amount of borehole drilling. It also reduces the drainage costs, increases the gas drainage from the coal matrix, enhances the non-stop production of the mine due to unsafe conditions, provides the mine working with safer conditions, and extracts the coal seams with high gas contents that were previously non-extractable [2]. Various investigations have been conducted by researchers on the coal degasification process. For example, Moll studied the degasification system in coal mines by optimizing the efficiency of the ventilation system and maximizing methane gas recovery. Therefore, in addition to analyzing the factors affecting the efficiency of methane drainage operations, the suitable location of drainage boreholes has been investigated and their proper drilling method has been evaluated with the aim of maximizing coal gas extraction [3]. Ramaswamy introduced a mechanism for selecting the most appropriate drilling pattern for boreholes' drainage system and coalbed methane (CBM) by a three-dimensional simulation approach. He studied methane emission percentages considering various geological, hydrogeological, operational factors, drilling methods, spatial boreholes location patterns, and boreholes distance [4]. Huang et al. determined the appropriate location for gas drainage boreholes at the Huainan mine in China. This suitable location has led to extended production periods and higher levels of gas production [5]. Kiem et al. investigated the gas content of coal seams in southern China Shanxi province. They used COMET3 software to design the appropriate patterns (horizontal, vertical, branch, and leaf) and adequate distance for suitable arrangements of the boreholes to produce maximum methane gas considering the coal permeability [6]. Black investigated the relationship between gas volume produced from the horizontal boreholes in coal seam, considering the coal seam properties and operational parameters. Their founding has shown that degree of saturation and drainage time greatly influence on the amount of gas production [2]. Gentzis analyzed the stability of horizontal drainage boreholes in the San Juan region at 3000 feet using STABView and FLAC software [7]. Lian studied the angle of boreholes, drilling type, and the diameter of the borehole to improve the degasification system in coal mines [8]. Zhang et al. evaluated the methane drainage from gob gas vent holes and estimated the most appropriate drilling depth of the drainage borehole in longwall mining [9]. Ding et al. simulated the gas flow from gob gas vent holes in a mine in China. They estimated the gas suction pressure, the appropriate distance between these gob gas vent holes, and the borehole diameter. Moreover, their relationship to methane recovery has been analyzed based on the ventilation and drainage systems [10]. Haisheng and Kuijun modeled the gas flow rate around the boreholes based on Klikenberg's law using Comsol software [11].

Zhou et al. optimized the design of drainage boreholes and the methane transmission network lines extracted from coal mines. They considered the gained profit from the methane production cycle as the objective function and concluded that the proposed optimization method improves gas production and increases profits [12]. Taheri et al. studied the impact of macerals on the level of methane emission from a coal block using Comsol software [13]. Xing and Zhang optimized the distances between drainage boreholes to reduce the gas content in the coal seam. They used FLAC3D to investigate the borehole stability due to permeability and porosity variation of the coal bed [14]. Qin et al. measured the effective radius of borehole drainage in the coal seam of the Kaiyuan mine (No. 9) using two models of pressure and gas flow. They showed that the effective drainage radius in this coal seam is 0.75 m and 1.5 m after 27 and 92 days of drainage, respectively [15]. Wei et al. determined the effective radius of drainage boreholes using Comsol software. They studied the single and multiple boreholes by considering the creep of the coal seam [16]. Guo et al. studied the optimal design of acidizing of CBM wells in Hancheng block China. They proposed a forward model and an inversion algorithm to diagnose the gas plugging [17].

Liu et al. developed a gas flow numerical model with an air leakage process based on in-situ measurement of gas drainage data. The modeling results have been shown that changing the permeability around the borehole may be a wise plan to control air leakage [18].

Fan et al. developed a finite difference numerical model based compositional flow model in coal seam by combining the gas mixture flow in fracture, the methane in coal matrix, mass transfer, and dynamic permeability [19].

This research aims to propose a proper design of horizontal drainage borehole patterns inside the coal seam in the Tabas coal mine, Iran. The numerical modeling was done by Comsol software.

2. Tabas coal mine (case study)

The Tabas coal mine is located 85 km from Tabas city. This mine is the only mechanized coal mine in Iran that is extracted as a retreat longwall mining. The panel dimensions are 220 m in width and 1200 m in length (Fig. 1). The coal seam thickness is about 1.8–3 m. The gas content of C1 coal seams in the Tabas coal mine is high and varies from 10 cubic meters per ton at a depth of 100 m to about 20 cubic meters at a depth of 600 m, and this has caused problems for coal extraction at the deep depth. The post-drainage operation is performing in the Tabas coal mine to deal with this issue. The reasons for using post-drainage method are: the coal seam has a low dip, and the depth of the coal seam increases with coal extraction. Therefore, drilling from the surface is not cost-effective due to its great depth. Another reason for using this method is low permeability and high gas adsorption of the coal seam [19]. Thus, in the Tabas mechanized coal mine, methane drainage started from the E3 panel. In this mine, the gas drainage method of cross-measure boreholes is being carried out by drilling six boreholes from a station inside the tailgate at an angle of 32–47° to the tailgate axis at the coal seam roof of the caved zone. The distance between methane drainage stations in the E3 panel varied between 18 and 22 m. In this mine, to increase the methane drainage efficiency and reduce the occurrence of outburst phenomenon, gas drainage from inside the coal seam is being planned. Therefore, this research has been done for selecting the feasible horizontal design boreholes inside the coal seam.

3. Numerical modeling of methane gas boreholes in a coal seam

Coal can contain methane gas in two forms free and adsorbed gas. Free gas exists in fractures and delicate joints of coal. The behavior of this gas is described by Boyle's law and the kinetic theory of gases. Also, the gas molecules are adsorbed to the surface of the coal, and its amount varies from 20 to 200 g per cubic centimeter.

At the natural pressure of the coalbed, about 90–95% of the total gas is adsorbed, and there is a natural transition between the free gas and the adsorbed gas. The amount of adsorbed gas depends on the equilibrium of free gas pressure in the isothermal environment. The Langmuir's law is used to describe the process of methane desorption and adsorption. In equilibrium, there is a unique relationship between the amount of gas adsorption and the free gas pressure by the Langmuir equation, given in Equation (1) [11,16].

$$C_p=\frac{\mathrm{A\,B}\,P}{1+\mathrm{B}P} \tag{1}$$

where C_p is the amount of gas desorption at a P pressure (cm^3/cm^3) from coal and is usually expressed as m^3/ton of coal. The coefficients A and B are Langmuir constants in units of cm^3/cm^3, m^3/ton, and kPa^{-1} and have different values for different coals in terms of type, temperature, and moisture content. Also, the amount of gas adsorption and desorption in equilibrium conditions is expressed by the Langmuir equation (Equation (2)).

$$V_E=\frac{V\infty P}{P+PL} \tag{2}$$

where $V\infty$ is Langmuir constant volume (kg/m^3), V_E is isotherm equilibrium (kg/m^3), and PL is Langmuir pressure (Pa). In the Langmuir equation, the method of adsorption and desorption of gas in coal

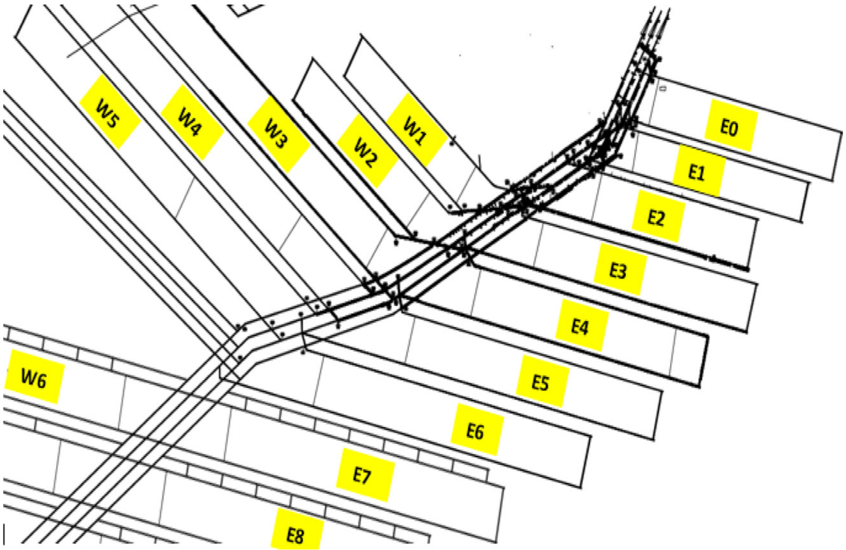

Fig. 1. The Tabas coal mine plan.

is described, and the resulting curve is called adsorption isotherm.

The mechanism of methane flow in coal is a combination of several complex processes commonly used to model this motion by Darcy's and Fick's laws. In this research, Fick's law was used in numerical modeling. Methane gas moves to gas drainage wells after diffusion. Also, the emitted flow under a concentration gradient is carried out by Fick's law, which is explained in Equation (3).

$$q_f = -DA_s\frac{\delta C}{\delta x} \tag{3}$$

where A_s is the cross-sectional area of methane gas path (cm^2), C is the gas concentration (cm^3/cm^3), D is diffusion coefficient (cm/s), and x is the flow direction.

The finite volume method is the most common in computational fluid dynamics (CFD). The use of CFD to predict internal and external fluid flows has made significant progress in the last three decades. Comsol Multiphysics (a finite element software) has high power in solving complex problems of fluid flow, heat transfer, mass transfer, chemical reactors, and electromagnetism [20]. This software can model the methane drainage boreholes according to the methane diffusion in the coal seam. The governing equations are related to fluid movement in a porous media considering the permeability and porosity of coal, the methane diffusion coefficient, the methane concentration, and the flow of methane gas molecules inside a coal block. The following hypotheses were considered in the numerical modeling of methane drainage from Tabas coal seams:

- The coal matrix is modeled as a rectangular block, and drainage boreholes are designed to discharge the coal seam gas.
- By performing methane drainage operations, the coal matrix does not shrink.
- Methane is uniformly distributed throughout the coal.
- Coal is free of water and other gases.
- In order to ignore air leakage, the isolation system is considered.

4. The model geometry for the borehole patterns

To determine the optimal drainage pattern inside a coal seam, three types of rectangular, hexagonal, parallelogram, and triangular patterns have been considered, as shown in Fig. 2.

It should be noted that borehole diameters of 76, 86, and 96 mm are modeled for all three arrangements. In all models, the coal block is considered a rectangle with a length of 20 m and a height of 3 m containing ten drainage boreholes. According to the previous numerical modeling, horizontal and vertical distances between the boreholes are considered 4 and 1 m, respectively [16]. Fig. 3 shows a coal block with ten drainage boreholes.

4.1. Material properties for the model

The material characteristics of coal and gas are given in Tables 1 and 2. The methane gas properties are selected directly from the software library because it has some fixed characteristics. Still, as the coal parameters are different in each area, the

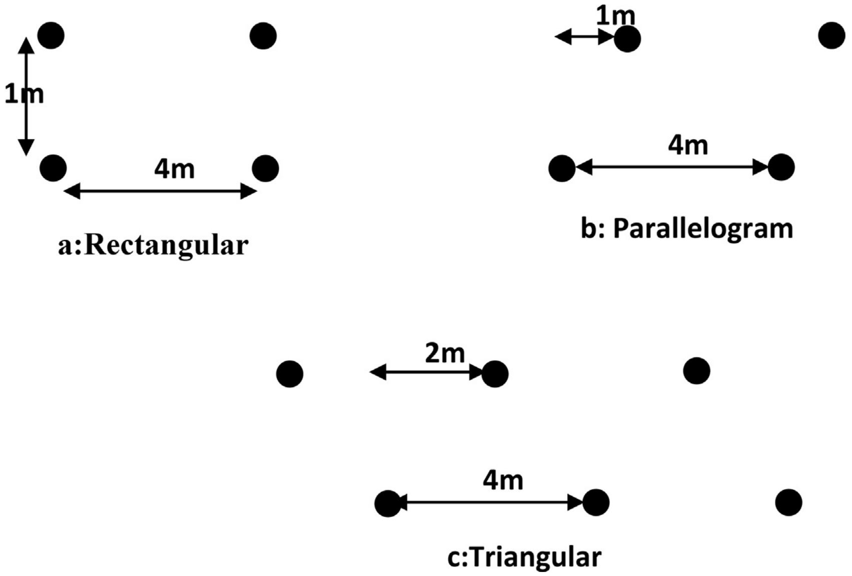

Fig. 2. Three geometries of boreholes patterns a) Rectangular, b) Parallelogram, and c) Triangular.

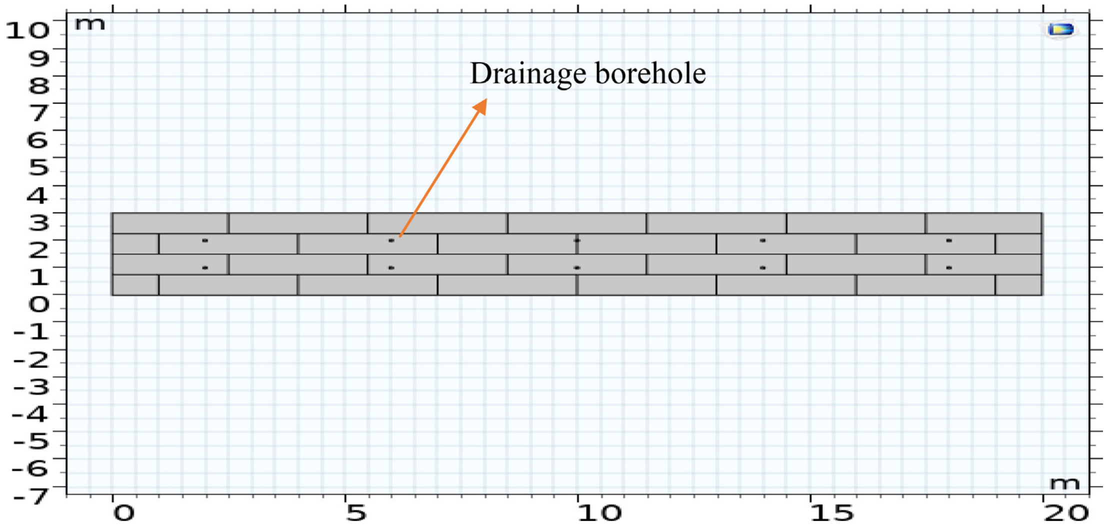

Fig. 3. A coal block with 10 drainage boreholes modelled in Comsol software.

Table 1. Methane gas specifications [21].

Parameter	Define the parameter in the software	Unit
Dynamic viscosity	eta_gas_2(T[1/K])[Pa s]	Pa s
Thermal conductivity	k_gas_2(T[1/K])[W/(m K)]	W/(m K)
Heat capacity at constant pressure	C_gas_2(T[1/K])[J/(kg K)]	J/(kg K)
HC (heat capacity)	*HC*_gas_2(T[1/K])[J/(mol K)]	J/(mol K)
VP (vapor pressure)	*VP*(T[1/K])[Pa]	Pa
Density	0.66	kg/m^3

Table 2. Coal seam properties in the Tabas Coal mine.

Parameter	Value	Unit
Porosity	0.069	1
Density	1360	kg/m^3
Poisson ratio	0.35	1
Permeability	$5\ 10^{-15}$	m^2

properties of Tabas coal seam should be entered into the software separately. The coal characteristics are defined for the model in the blank material section.

To model the fluid motion inside the coal seam, the porous media fluid module has been selected in Comsol. This module follows the equation and Fick's law. The methane gas flow inside the coal seam is modeled by entering the characteristics of coal and methane gas, the Langmuir constant, the maximum absorption of Langmuir, the coal concentration matrix, and the suction pressure in the borehole head. This research investigates the movement of methane gas inside the coal block and its concentration changes. Therefore, the option of "transport of diluted species (TDS)" in porous media is selected from the chemical species transport section. Moreover, since gas concentrations change with time, this treatment should be considered, as a time-dependent process. The input parameters to the model are given in Table 3. The average gas concentration in the coal was evaluated as 12 cubic meters per ton of coal. Also, the walls of the coal block are regarded as having no flux. After that, the constructed model is meshed in Comsol software and used for analysis.

4.2. Numerical modeling scenarios for methane drainage boreholes

According to the three types of patterns and three different borehole diameters, nine numerical models were implemented in Comsol software, and the results have been analyzed. In the following section, the model results are described for rectangular patterns with a borehole diameter of 76 mm, then the results of all the scenarios are explained and tabulated in Table 5.

4.2.1. Rectangular patterns with a borehole diameter of 76 mm

In the first scenario, the diameter of the boreholes is 76 mm. Also, the boreholes have a rectangular pattern with a distance of 4 m. The methane

Table 3. Input parameters to the numerical model in Comsol.

Parameter name	Symbol	Value
Density	*n*	671 [mol/m^3]
Global gas constant	*R*	8.314 [J/(mol K)]
Temperature	*T*	293.15 [K]
Maximum internal pressure	P_ max	1.5 [MPa]
Borehole suction pressure	P _ out	−5 [kPa]

Table 4. Changes in gas volumes before and after the gas drainage process in the coal block.

Description	Value
The initial amount of methane gas in the coal block (m^3)	974.953
The gas remained in the coal after 180 days of drainage (m^3)	204.269
The gas extracted from the coal after 180 days of drainage (m^3)	770.684

Table 5. Summary of drainage results in different boreholes' diameters and patterns.

Diameter (mm)		Rectangle	Parallelogram	Triangle
76	Suitable gas drainage time (days)	88	77.5	76.5
	Amount of drained gas (m^3)	682.08	681.87	681.778
86	Suitable gas drainage time (days)	84.5	74.5	73.5
	Amount of drained gas (m^3)	681.49	682.03	681.998
96	Suitable gas drainage time (days)	82	71.5	70.5
	Amount of drained gas (m^3)	682.03	681.33	681.27

concentration contour around the borehole is obtained by running model, as shown in Fig. 4.

According to this figure, the methane concentration around the drainage boreholes decreases as the borehole distances increase. The variations of methane concentration in the initial condition and after 180 days of gas drainage are shown in Figs. 5 and 6. According to Fig. 5, it can be stated that the methane concentration is high in places far from the location of boreholes.

In this research the amount of gas drainage has been calculated with time by integration from the model surface. The results are presented in Table 4.

Gas flow changes in the coal block are shown in Fig. 7. According to this figure, the graph is exponential, which indicates a decrease in the amount of drained methane gas over time.

The minimum hazard limit for methane gas in the Tabas coal mine is 1.25%, which shows that if the concentration of methane gas is less than 30% of its initial concentration in the coal block, there is a risk of gas explosion in the mine. Therefore, when the concentration of methane gas reaches 30% of its initial concentration, the maximum appropriate time for methane gas drainage is achieved.

The maximum duration of gas drainage from a borehole will be 88 days according to numerical modeling results. At this time, 682.08 m^3 of the methane gas has been drained.

4.3. The modeling results of all nine scenarios

In this research, nine different scenarios are considered for the numerical modeling of the coal drainage process in the Tabas coal mine. Table 5 summarizes the number of suitable drainage days and the amount of gas drained in each of the nine scenarios.

The methane drainage rates of the boreholes are calculated by dividing the amount (volume) of drained gas by the number of suitable drainage days (Table 6).

The most important results (from Tables 5 and 6) can be summarized as follows:

- According to Tables 5 and 6, the performance of boreholes in the triangle pattern is better than the other patterns. Because the adequate radius overlaps of drainage boreholes are less than the different patterns. Moreover, according

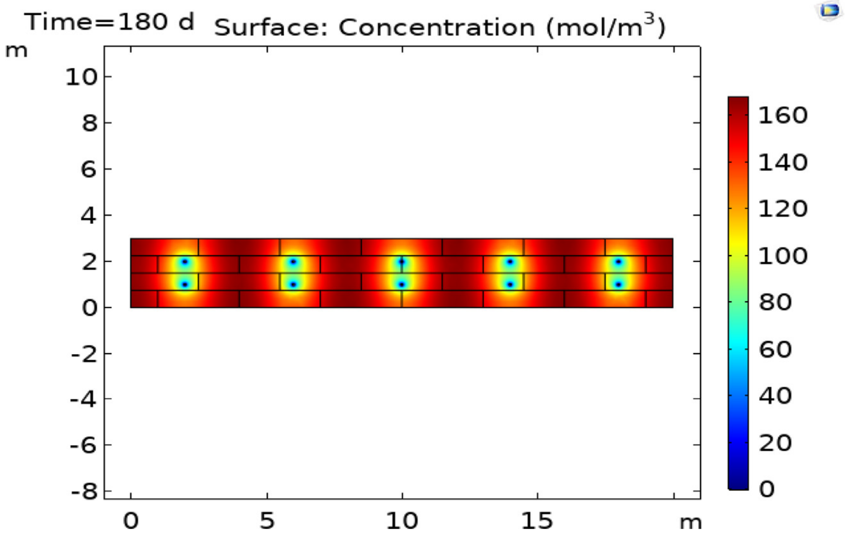

Fig. 4. Methane concentration contours for rectangular patterns with a borehole diameter of 76 mm.

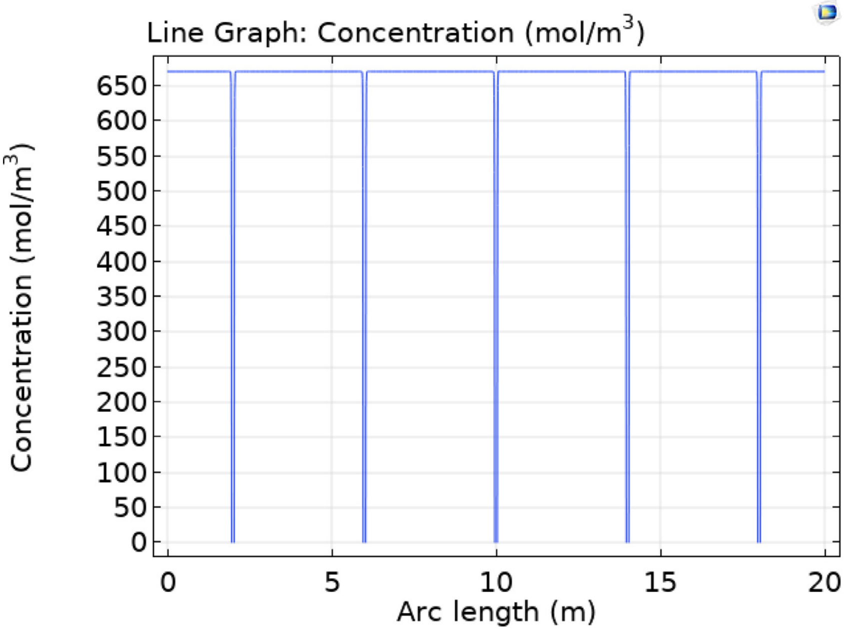

Fig. 5. Methane concentration in coal block in the initial condition.

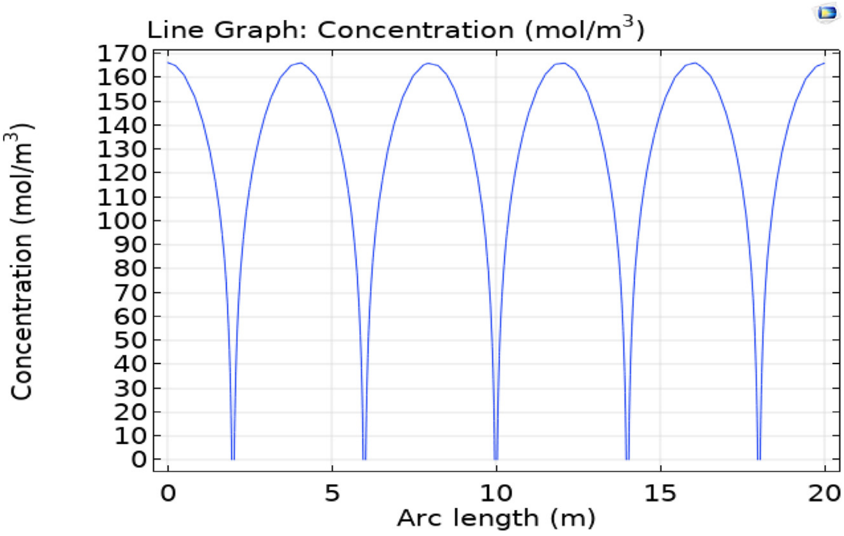

Fig. 6. Methane concentration in coal block after 180 days of gas drainage.

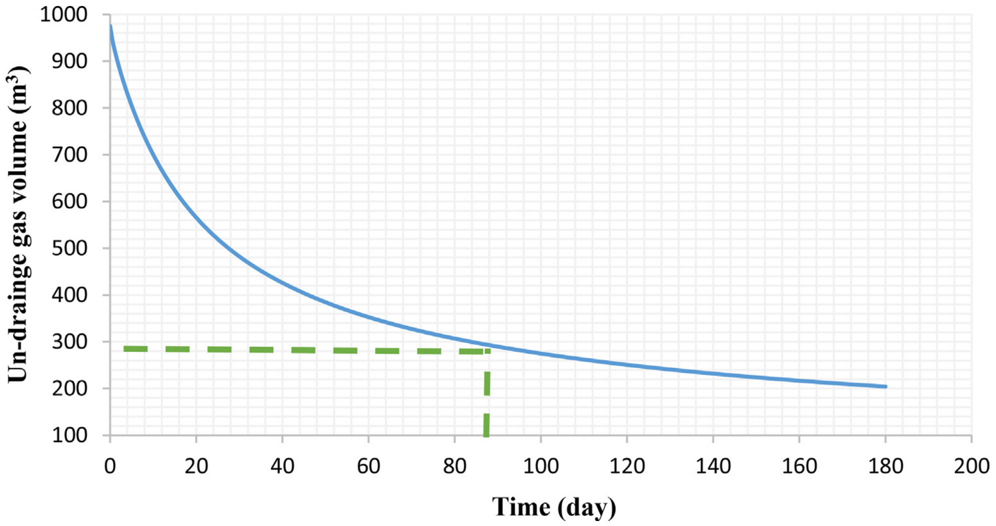

Fig. 7. Changes in gas volume of coal block over time.

Table 6. Methane drainage rates of boreholes (m^3/day) for the nine modelled scenarios in Comsol.

Diameter (mm)	Rectangle	Parallelogram	Triangle
76	7.75	8.8	8.91
86	8.07	9.16	9.28
96	8.317	9.53	9.66

to Table 5, in boreholes with the same diameter, suitable gas drainage time in the triangle pattern is less than in the other patterns.

- By comparing the data in Table 6, it is concluded that in boreholes with the same diameter, the gas drainage rate in the triangle pattern is higher than in two other patterns. Therefore, it is concluded that the performance of the boreholes in the triangle pattern is more effective than in the other two patterns.
- According to the results in Table 5, it is concluded that suitable gas drainage time for a borehole with a 96 mm diameter in the triangle pattern is less than the other two patterns.
- The relationship between gas drainage rate and borehole diameter is shown in Fig. 8. According to this figure, the relationship between borehole diameter and gas drainage rate is linear. The

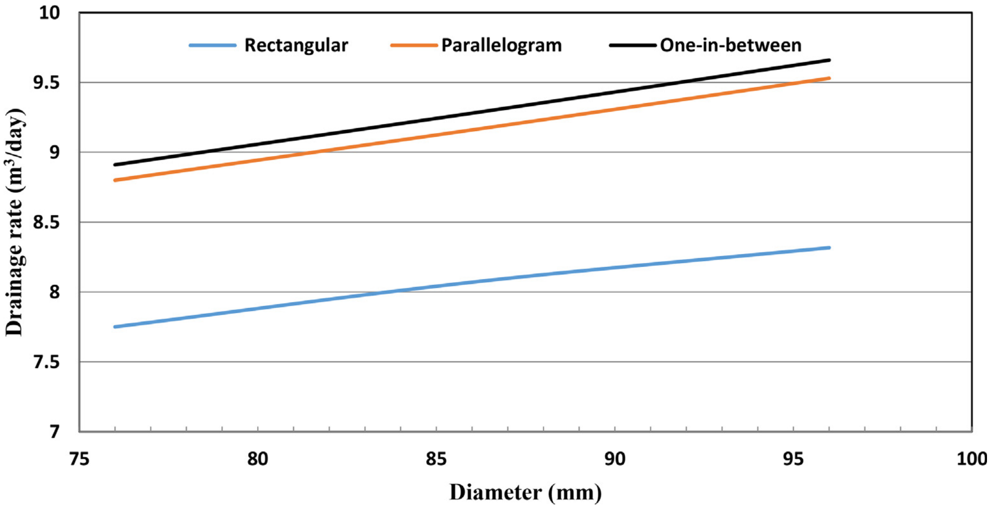

Fig. 8. The relationship between gas drainage rate and borehole diameter in scenario 1.

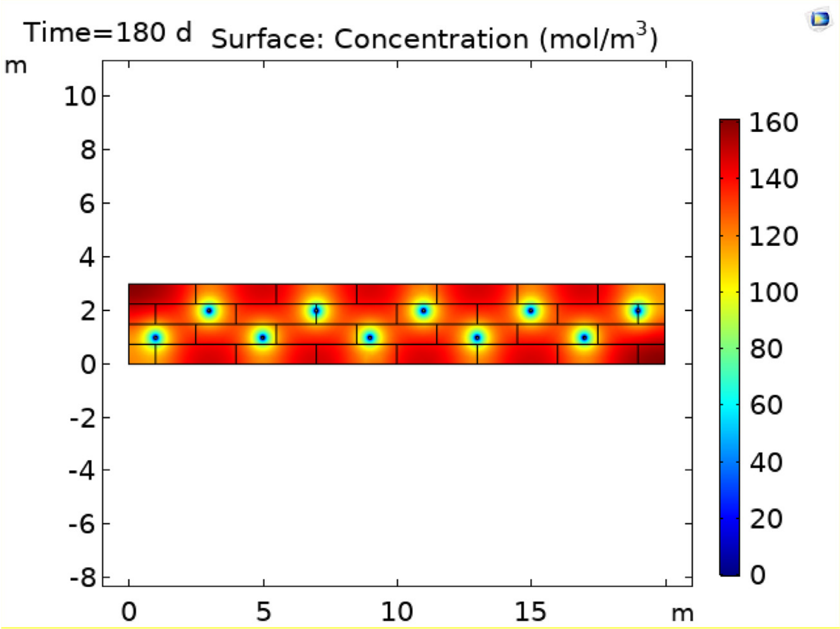

Fig. 9. Methane concentration in a triangular pattern (96 mm diameter).

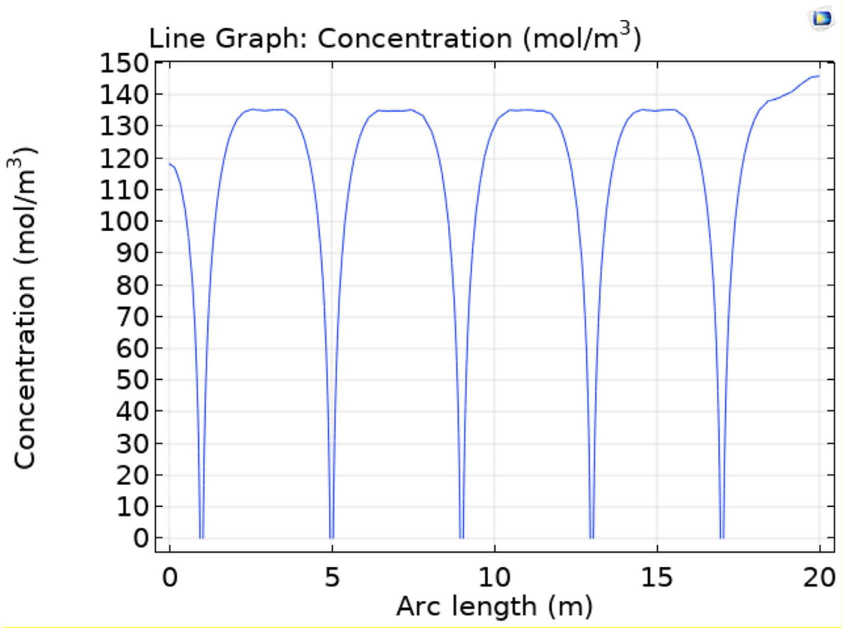

Fig. 10. Methane concentration in the coal block after 180 days of gas drainage using a triangular pattern of boreholes with 96 mm in diameter.

Table 7. Sensitivity analysis of coal porosity.

The ratio of the porosity to initial porosity	0.8	0.9	1.1	1.2	1.3	1.5
Suitable gas drainage time (days)	92.5	80	63	56.5	51.5	43.5
Amount of drained gas (m^3)	681.358	681.258	681.54	680.829	681.215	681.125
Drainage rate (m^3/day)	7.37	8.52	10.82	12.05	13.23	15.66

drainage rates in the triangle and parallelogram patterns are relatively the same. However, the difference between the results gained from these two patterns and those obtained from the rectangular pattern is considerable. Therefore, it can be concluded that the rectangular pattern is not suitable for gas drainage boreholes.

By comparing the data in Table 6, the borehole with a diameter of 96 mm with an average drainage rate of 9.66 m^3/day has a higher average drainage rate than other boreholes. Therefore, a borehole with a diameter of 96 mm is a more suitable diameter for gas drainage in the triangular pattern. Finally, the triangle pattern is more suitable for the

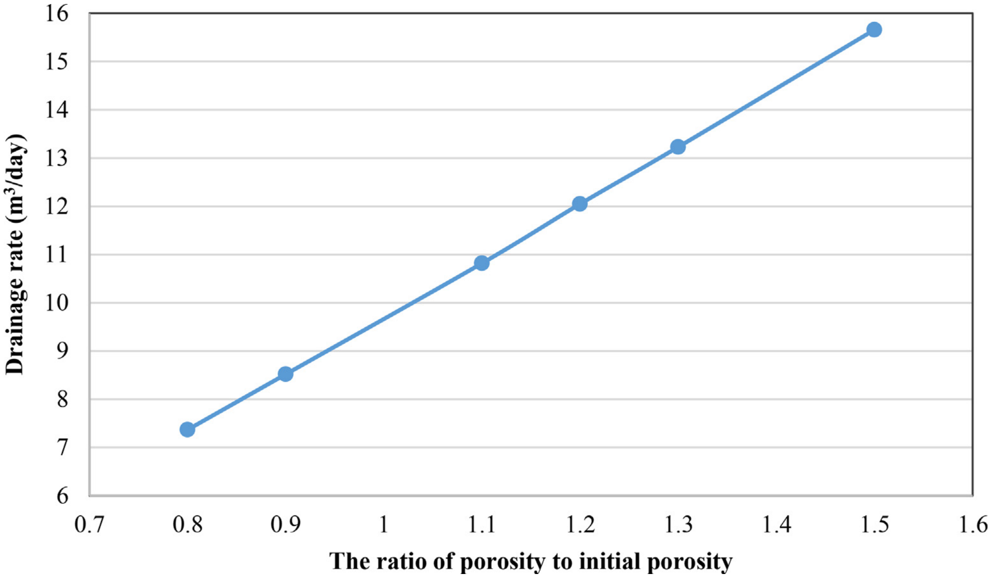

Fig. 11. The effect of porosity on methane drainage rate.

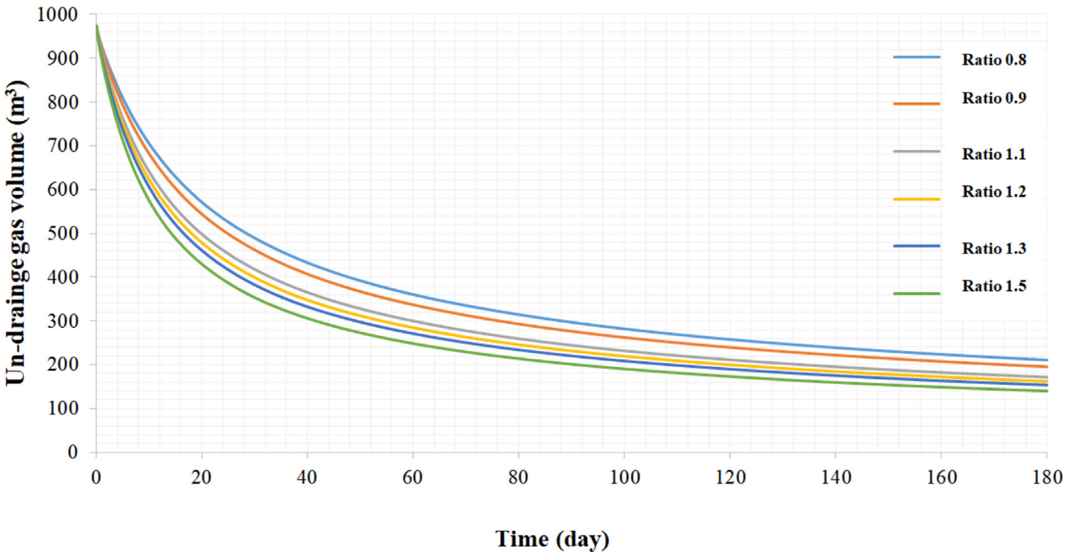

Fig. 12. The effect of porosity on drained gas flow.

Tabas coal mine among the three patterns considered in this research. The methane concentration contour around the borehole in the triangular pattern is shown in Fig. 9. The variations in methane concentration after 180 days of gas drainage are shown in Fig. 10.

5. Sensitivity analysis

Coal porosity is one of the most essential factors in methane drainage operation. To evaluate the effect of coal porosity on drainage rate, a triangle pattern with a borehole diameter of 96 mm with different coal porosities has been studied. The results of the sensitivity analysis are presented in Table 7.

The effect of porosity on gas drainage rate and volume of drained gas is shown in Figs. 11 and 12.

According to Fig. 10, a positive linear relationship between the drainage rate and porosity exists. Also, according to Fig. 11, increasing the coal seam's porosity, the volume of un-drainage gas decreased. Therefore, it can be concluded that the volume of gas drainage can be increased by increasing the effective porosity of the coal seam by hydraulic fracture operation in the coal seam, which increases the coal seam permeability.

6. Conclusion

In this research, the design of an appropriate pattern of horizontal drainage boreholes inside the coal seam in the Tabas coal mine was performed using Comsol software. Therefore, the reduction of methane concentration during the drainage process was investigated. The following main conclusions can be gained from this study:

- This model is fundamental and applicable for mine with high gas content.
- Based on this model, the necessary ventilation can be designed to remove the remaining gases in the coal seam emitted to the entry.
- To design the proper pattern of the boreholes, nine scenarios are considered.

According to the CFD modeling, the most important results are as follows:

- Based on the two criteria of minimizing drainage day and maximizing gas drainage rate until the methane concentration reaches 30% of its initial value in the coal block, the triangular pattern of boreholes with 96 mm in diameter is selected as a suitable pattern in the Tabas coal mine.
- The average gas drainage rate for this case is 9.66 m^3/day, and in 70 days—681.27 m^3 of gas has been drained from a coal block of 20 m in length and 3 mm in height.

The results of sensitivity analysis showed a positive linear relationship between drainage rate and the ratio of primary and secondary porosity of coal. These results also showed that increasing the coal seam's porosity, the volume (flow) of un-drainage gas decreased.

Ethical statement

The authors state that the research was conducted according to ethical standards.

Funding body

None.

Availability data and material

All data and models generated or used during the study appear in the submitted article.

Conflicts of interest

The authors declare that there is no conflict of interest.

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