Journal of Engineering Science and Technology Review 11 (2) (2018) 54 - 62

Research Article

JOURNAL OF
Engineering Science and Technology Review

www.jestr.org

Optimization of the Surface Vertical Well of Abandoned Mine Goafs based on Gas Seepage Characteristics

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Received 3 February 2018; Accepted 19 April 2018

Abstract

Abundant residual methane stored in abandoned mine goafs can be effectively extracted by surface vertical wells. However, abandoned mine goafs are in a closed state and are not influenced by underground ventilation systems, which differentiate them from production mine goafs. Thus, the studies on the optimization of surface vertical well location in production mines cannot be directly used to guide methane extraction in abandoned mine goafs. To determine a reasonable location for surface vertical well in abandoned mine goafs, this study, based on the mathematical model of methane seepage in an abandoned mine goaf, employed the COMSOL software to numerically explore methane seepage characteristics in the goaf under the conditions of four typical vertical wells. The well locations included central position of goaf, middle of the boundary in the trending direction of goaf, middle of the boundary in the inclination direction of goaf, and corner position of goaf. The methane seepage characteristics of the goaf in the 3D, 2D, and 1D flow fields were analyzed separately, and the high-speed flow zones in the goaf were divided. The optimal well location for extraction was determined based on the methane seepage characteristics and the range of high-speed flow zone. Results indicate that under the conditions of surface vertical well, methane in the goaf initially flows slowly into the high-speed flow zone and then rapidly to the well location under the negative pressure of the drainage. The corner position of goaf is the best well location. The maximum methane flow velocities in the upper and lower parts of the goaf under the conditions of the well location are more than 2.05 times of those under other well locations. The weak belt of the surface vertical well is in the range of 0-10 m from the bottom of the goaf. Methane flow velocities in this area are only 0.035–0.28 m/s under the four well conditions. The control effect of single-well on methane flow in the goaf is limited, and the goaf has blind areas for drainage under the single-well condition. The conclusions provide a theoretical reference for the layout and optimization of surface vertical well locations in abandoned mine goafs.

Keywords: Abandoned mine goaf; Seepage characteristic; High-speed flow zone; Well position

1. Introduction

Coal is one of the most important resources in the world apart from natural gas and oil because of its reliability and affordability [1]. More than 35% of global coal is produced in China, where 90% of the coal mines are underground mines, and 51% are highly gassy mines [2-3]. Long periods of high-intensity mining activities have resulted in many abandoned mines as well as abandoned mine goafs underground. More than 620 large-scale coal mines have been closed in China, where stored methane is estimated to be in the hundreds of billions of m^3. Methane in abandoned mine goafs leads to a series of environmental, economic, and safety problems, such as continuous mine fires and greenhouse effect. Nonetheless, goaf methane is premium clean energy whose calorific value is equivalent to natural gas, and no harmful substance is produced after it is burned. Thus, methane extraction from abandoned mine goafs can not only solve the safety problems caused by methane accumulation but also produce considerable economic benefits.

The performance of surface vertical well varies greatly in different positions, even in the same coal field. Therefore, selecting a reasonable well position is the core problem of methane extraction in abandoned goafs by surface vertical well. Existing studies mainly concentrate on the law of methane seepage in mined-out areas and the optimization of well position of production mines, and often disregard the unique characteristics of abandoned mine goafs. An abandoned mine goaf is a relatively independent system without the influence of a mine ventilation system, which differentiates it from a production mine goaf. In addition, the movement of overlying rock formations in abandoned mines has stabilized; the middle of the goaf has re-compacted due to the vertical stress transferred from the coal rock mass above the goaf. Mining cracks have reclosed under high stress, which leads to some differences in methane seepage characteristics between abandoned mine goafs and production mine goafs. Although the relevant studies can be used to guide methane extraction and well position in production mine goafs, they cannot be fully applied to methane extraction from abandoned mine goafs. At the same time, current studies on the use of methane in abandoned mine goafs mainly focus on resource evaluation, reserve forecasting, and exploitation prospect evaluation. The characteristics of methane seepage in abandoned mine goafs

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ISSN: 1791-2377
doi:10.25103/jestr.112.09

under conditions of surface vertical well are not considered fully, and they are key factors in determining the well position in the field construction.

To determine the best position of surface vertical well in an abandoned mine goaf, a model of methane seepage in an abandoned mine goaf under surface well condition was established based on the characteristics of abandoned mine goafs. The methane seepage characteristics in the goaf under different wells conditions were studied to provide the theoretical basis for optimizing the surface vertical well location in an abandoned mine goaf.

2. State of the art

Methane in abandoned mine goafs is a resource that has gradually attracted research attention in recent years, and related studies on its utilization are still in the initial stage. At present, scholars have conducted some studies on the sources of methane and the influencing factors of methane distribution in abandoned mine goafs by using theoretical analysis and on-site industrial tests. Some reserve forecasting models have been presented, but these studies mainly focused on resource evaluation, resource forecasting, and exploitation prospect evaluation. For example, Qin et al. [11] established a composite model based on the effect of "three belts" on the methane in an abandoned goaf and simulated the law of methane production over time. The methane source of the abandoned goaf was analyzed according to the prediction results. Karacan [12] used a statistical method to establish a composite analysis model based on actual point data of methane production from different wells. The results showed that wells located at low coal recovery rates areas have high methane production. Karacan et al. [13] proceeded from the factors affecting the methane reserves in abandoned mine goafs and summarized the existing methane utilization methods in goafs and the status of methane extraction in major coal-producing countries. The effects of drainage methods, mine tightness, and other factors on methane production were analyzed. Palchik et al. [9] focused on the influence of address conditions on methane production performance. They used mathematical statistics and mathematical analysis methods to analyze the characteristics of time and volume of methane emission from an abandoned mine goaf under three geological conditions and successfully estimated the methane production in shallow abandoned goafs. Shi et al. established a new methane pressure prediction model by using source pressure and time constant and successfully verified the results of the model in two abandoned mines in Europe. The above studies analyzed and evaluated the state of methane in abandoned mine goafs from the perspective of methane reserves, methane pressure, and exploitation prospects. However, they did not study from the perspective of methane migration under surface vertical well conditions. Thus, The conclusions of the studies have limited guidance on the placement of surface vertical well. The essence of methane drainage is the migration of methane. The transport law of methane in goafs must be clearly defined firstly when determining the best location for well.

Owing to the special geological conditions of goafs, scholars use numerical simulation methods to study the migration of methane in goafs. For example, Qin et al. [15] considered the influence of different factors on the effect of drilling drainage and established a CFD model that combines the gas permeability and methane release characteristics of the goaf. The methane distribution in the goaf was simulated, and the results showed that the methane production is related to the methane release source, the height of the goaf, and the well position. Zhao et al. [16] classified the goaf into turbulent, transitional, and seepage areas according to the different degrees of collapse of overlying strata and the capacity of methane passing after coal mining. They also used a commercial CFD (Computational Fluid Dynamics) software to study the methane flow characteristics in a longwall face. Kurnia et al. [17] established a CFD model that is highly consistent with the underground roadway and where the ventilation network is optimized based on the air distribution and methane concentration in the goaf. Through an experiment, Li et al. [18] found that the shape of the goaf is an elliptic paraboloid and then studied the methane migration rule in this ellipsoid sphere. Their results showed that permeability in the goaf is between $1.5\times10^{-6}\mathrm{m}^2$ to $6.0\times10^{-6}\mathrm{m}^2$. Zhang et al. [19] considered the effect of different methane release sources on methane in a goaf. Methane flow in the goaf under the condition of "U+L" ventilation was studied. The results showed that the best methane drainage point changes with the advancement of the working face. However, the objects studied by the above scholars are production mine goafs under the mine ventilation system. The inlet and return roadways have a significant influence on methane flow in the goaf. An abandoned mine goaf is a relatively closed system. Thus, the law of methane migration in a production mine goaf cannot be completely applied to an abandoned mine goaf under negative pressure drainage.

The control equation of methane flow in the goaf is crucial for numerical calculation. Travis et al. [20] applied the basic theorem of thermodynamics to fluid flow to overcome the inability of traditional methane flow equations to couple with thermodynamics and developed CFD codes that more closely correspond to the actual state of the methane state equations. Wang et al. [21] attempted to solve the problems of complex methane flow equation in the mine goaf and the substantial use of computer resources. The methane flow equations in the goaf were established by using the conservation of mass equations and the pipe flow equations and were successfully applied to mines with U-shaped ventilation conditions. The above studies improved the computational efficiency to some extent and increased the applicability of the CFD model. However, these studies used the Navier–Stokes equation with fast flow velocity in the inlet and return roadways. Abandoned mine goafs are not affected by the mine ventilation system because the methane is transported to the wellhead by slow seepage under negative pressure drainage.

Therefore, to address the deficiencies of existing studies, this study established a mathematical model of methane seepage applicable to the abandoned mine goaf. The numerical simulation software COMSOL was used to study the law of methane migration under four typical well conditions: central position of goaf, middle of the boundary in the trending direction of goaf, middle of the boundary in the inclination direction of goaf, and corner position of goaf. The characteristics of methane migration under each well condition were compared, and the rule of velocity variation and the range of high-speed flow zone were analyzed. Finally, the best well position for the abandoned mine goaf was determined to provide theoretical guidance and basis for the field layout of surface vertical well.

The remainder of this study is organized as follows. Section 3 elaborates on the mathematical model of methane seepage and the finite element modeling method. Section 4 discusses the characteristics of methane and the range of high-speed flow zone under each well condition. Section 5 summarizes the conclusions.

3. Methodology

Methane seepage in an abandoned mine goaf can be described through the transport of fluids in porous media. First, a mathematical model was established based on the physical equations that followed by methane seepage, and then numerical models and boundary conditions were established based on the characteristics of the abandoned mine goaf.

3.1 Mathematical model

The total amount of methane in the extraction process remains unchanged. Thus, it obeys the law of conservation of mass. And the continuity equation was used to describe this law as follows:

$$\frac{\partial \rho}{\partial t} + div\left(\rho u\right) = 0 \tag{1}$$

where t is the time variable (s), ρ is the fluid density (kg/m3), and u is the velocity (m/s).

All low-velocity objects obey Newton's second law, and methane seepage in an abandoned mine goaf is no exception. The distribution of crack has great randomness. Thus, the porosity and permeability values at each point in the goaf are a function of space change. Fallen rock in the goaf have a hindered effect on methane flow. To describe this fluid flow in a heterogeneous porous media, the Brinkman equation was used, which is expressed as

$$\nabla u + \frac{\rho}{\varepsilon}\left(\frac{\partial u}{\partial t}\right) + \frac{u}{k}u = \nabla\left(\frac{u}{\varepsilon}\left(\nabla u + \nabla u^{t}\right)\right) + F_{\mathrm{a}} \tag{2}$$

where ρ is the fluid density (kg/m^2), is the permeability (m^2), F_a is the sum of the external force at this point (N), u is the seepage velocity (m/s), and t is the time variable (s).

Assuming that the methane abandoned mine goaf is an ideal gas, to ignore the volumetric forces among methane molecules that collide with one another, the ideal gas equation of state is as follows:

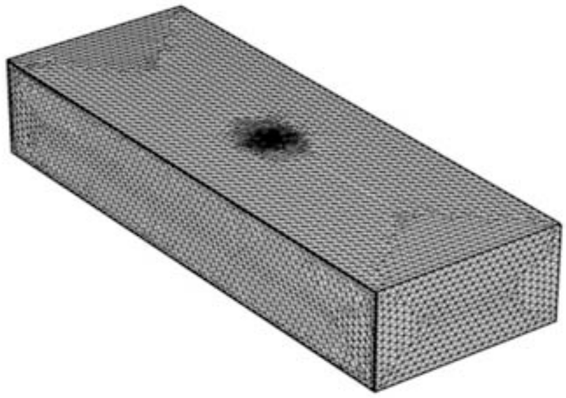
$$PV = \frac{m}{M}RT \tag{3}$$

where P is the pressure of methane (Pa), V is the methane volume (m^2), m is the mass of methane (kg), M is the molar mass of methane (m/s), and T is the absolute temperature (K).

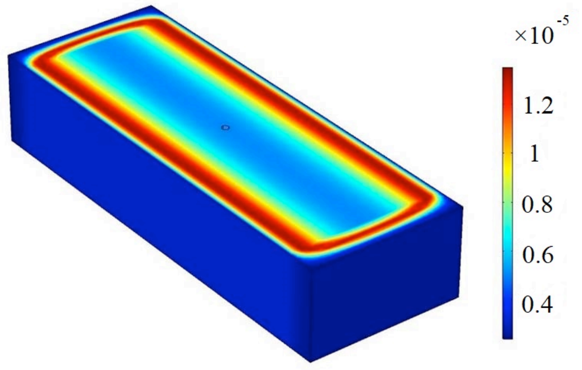
3.2 Finite element modeling

3.2.1 Geometric model and spatial distribution of permeability

In this study, the numerical model was established based on the prototype of the abandoned mine goaf formed by the mining of Yuecheng coal mine in Shanxi Province. The burial depth of the #3 coal seam of this coal mine is approximately 388 m, the average thickness of the coal seam is 6 m, and the coal seam is nearly horizontal. A numerical model of the abandoned goaf was established based on the measured parameters of the goaf geometric boundary.



(a) Geometric model



(b) Spatial distribution of permeability

Fig. 1. Model of Abandoned mine goaf

Figure 1 is the model of an abandoned mine goaf. The length of the model is the length of the goaf in the trending direction, the width is the length of the goaf in the inclination direction, and the height is the height of the crack zone in the goaf. The geometric dimensions of the model are length*width*height = 250 m*90 m*50 m. The fracture and settlement of overlying rock formations generate several mining cracks during the coal mining process. The interconnected cracks provide the channel for methane seepage. The fractures in the middle of the goaf are partially closed under vertical stress after the formation of the abandoned mine. Thus, the permeability at this location decreases. However, the permeability at the boundary of the goaf remains high because of the small vertical stress. Thus, an O-shaped hypertonic zone exists at the edge of the goaf [22]. Figure 1(b) shows the spatial distribution of permeability that was set based on this result.

3.2.2 Boundary conditions

In this study, the four commonly used surface vertical well positions (Fig. 2) were selected as study variables, specifically, central position of goaf, middle of the boundary in the trending direction of goaf, middle of the boundary in the inclination direction of goaf, and corner position of goaf. The wellbore was set as the pressure outlet, the boundaries around the model were set as the pressure inlet, and the upper and lower interfaces were set as wall surfaces.

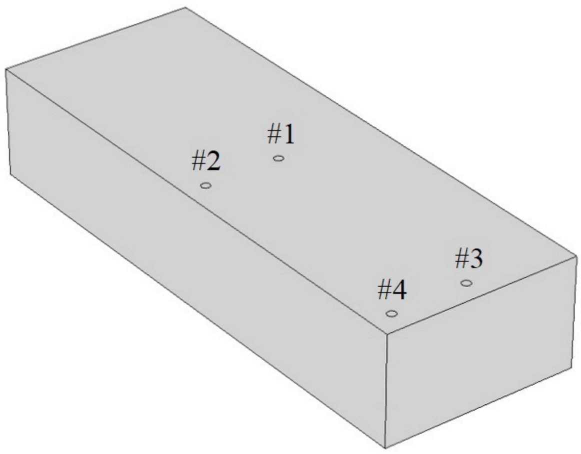


Fig. 2. Schematic of the surface vertical well position

The basic parameters of the model are shown in Table. 1..

Table. 1. Parameters of the numerical model

Parameters	Inlet pressure	Outlet pressure	Density	Dynamic viscosity coefficient
value	0	−1000	0.716	1.08×10^{6}
unit	Pa	Pa	kg/m^3	Pa*s

4. Analysis of results and discussion

4.1 Three-dimensional flow field

Vector graph and streamline graph can directly reflect the 3D flow direction and seepage path of methane in each point of the model. The density of a point streamline also reflects the methane flow velocity at this point.

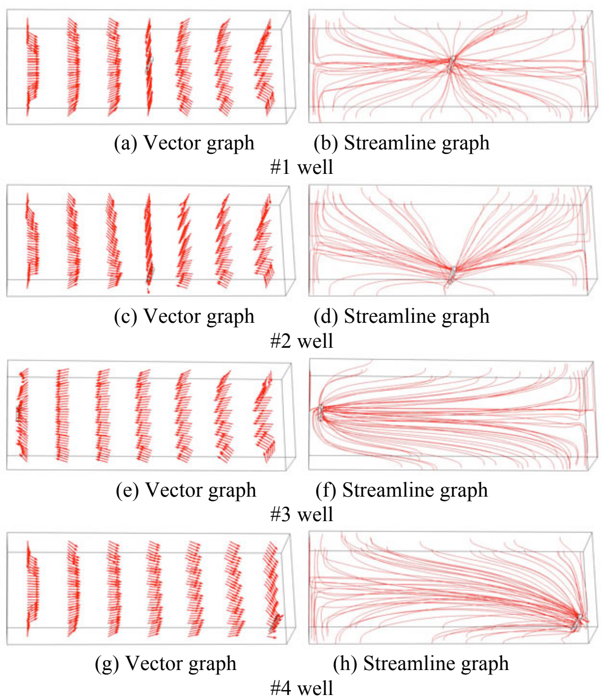


Fig. 3. 3D flow field under four surface vertical wells

Figure 3 shows the 3D flow field of the methane in the goaf under four surface vertical well conditions. The methane flows from the goaf to the vicinity of the well under the effect of negative pressure. Streamlines in the upper part of the goaf are denser than those in the bottom, showing that methane flows quickly from above the goaf to the well under the influence of negative pressure. Surface vertical well has a strong control effect on the upper part of the goaf and a relatively weak control on the lower part of the goaf.

4.2 Two-dimensional flow field

The layouts of the four surface vertical wells are the same in the vertical direction and only differ in the horizontal direction. Therefore, the velocity distribution in section diagrams of the x–y plane was selected for analysis, and the difference in the vertical direction was reflected by the planes of different z coordinates.

Figure 4 shows the distribution of methane velocity on different horizontal surfaces in the goaf under #1 well condition. Obvious high-speed areas of methane seepage are observed near the surface vertical well. The pattern of methane seepage distribution changes from the “O” to the “O–X” shape from the top to the bottom of the goaf. The maximum methane seepage velocity at the top of the goaf is 2.26 m/s, while that at the bottom is only 0.035 m/s. The two seepage speeds differ by two orders of magnitude. The closer to the bottom of the goaf, the greater the vertical stress in the mining cracks, the higher the closure of the cracks, and the greater the resistance to methane flow in the goaf. In addition, methane in the goaf flows from both the vertical and horizontal directions into the upper section of the surface vertical well. Methane flows into the lower section of the well only from the horizontal direction, thus the methane seepage velocity is significantly low in this area. The closer the methane is to the surface vertical well, the greater the methane seepage velocity, and the greater the distance of the methane from the bottom of the goaf, the more obvious is this trend.

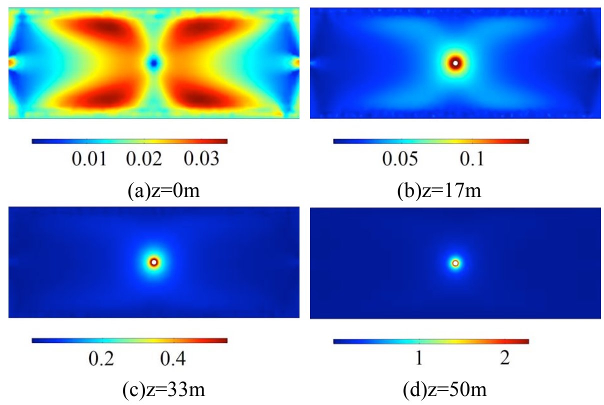


Fig. 4. Methane velocity distribution at different horizontal surfaces under #1 well condition

Figure 5 shows the distribution of methane velocity at different horizontal surfaces in the goaf under #2 well condition. The shape of the high-velocity zone of methane seepage from the top to the bottom of the goaf changes from “O” to “-”. The maximum methane seepage velocity at the top of the goaf is 4.6 m/s, while that at the bottom of the goaf is 0.06 m/s; these values are 2.03 and 1.71 times higher than the corresponding parameters under the #1 well condition. This discrepancy is caused by the high penetration rate and the small resistance to methane flow of the surface vertical well position, which, in turn, are attributed to the surface vertical well being in the area with high permeability and the small resistance of methane flow.

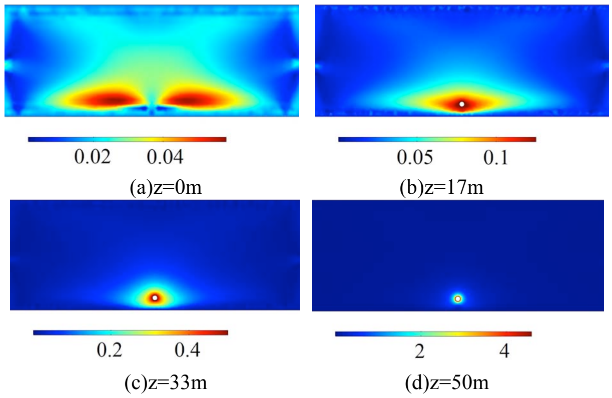


Fig. 5. Methane velocity distribution at different horizontal surfaces under #2 well condition

Figure 6 shows the distribution of methane velocity at different horizontal surfaces in the goaf under the #3 surface vertical well condition. The shape of the high-velocity zone of methane seepage from the top to the bottom of the goaf changes from “O” to “C”. The maximum methane seepage velocity at the top of the gob is 4.6 m/s, which is equivalent to the corresponding velocity under #2 well. The maximum methane seepage velocity at the bottom of the goaf is 0.085 m/s, which is equivalent to 2.4 times of that under the #1 well condition.

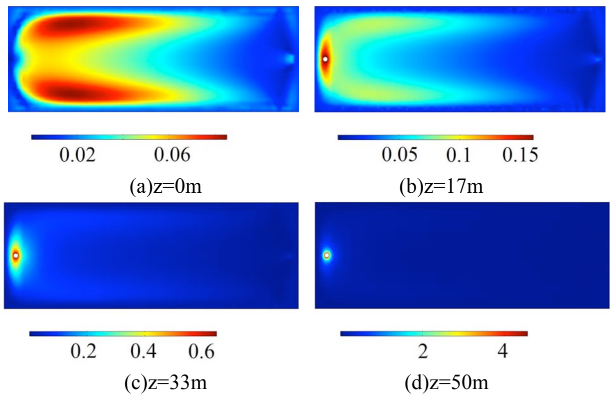
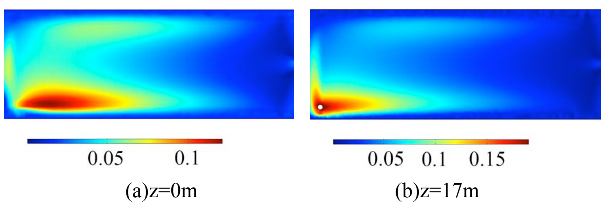


Fig. 6. Methane velocity distribution at different horizontal surfaces under #3 well condition

Figure 7 shows the distribution of methane velocity at different horizontal surfaces in the goaf under the #4 well condition. The shape of the high-velocity zone of methane seepage from the top to the bottom of the goaf changes from “O” to “L”. The maximum methane seepage velocity at the top plane of the gob is 4.5 m/s, which is equivalent to the corresponding velocity under the #2 and #3 well conditions. The maximum methane seepage velocity at the bottom of the goaf is 0.12 m/s, which is equivalent to 3.2 times of that under the #1 well condition. Thus, #4 well is significantly superior to the other three wells in controlling the bottom of the goaf.



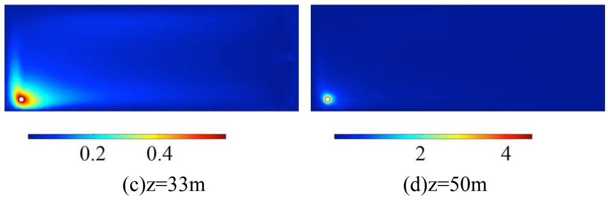


Fig. 7. Methane velocity distribution at different horizontal surfaces under #4 well condition

Figures 4 to 7 show that, under the four typical well conditions, the closer to the top of the goaf, the more concentrated the methane velocity distribution is, and the closer to the bottom of the goaf, the closer the shape of the high-velocity methane flow area is to the high-permeability zone at the edge of the goaf. In the upper part of the goaf, methane flow is mainly affected by the well location and in the lower part of the goaf, it is mainly affected by the spatial distribution of the permeability. Judging from the drainage effect, #1 well has the minimum control range for the goaf, and the methane seepage velocity under #1 well condition is significantly lower than the same plane under other well conditions . Under the #2, #3, and #4 well conditions, the maximum seepage velocity above the goaf is relatively close. However, the methane seepage velocity in the lower plane of the goaf has a large difference, and the maximum speed under #4 well is about twice that under #2.

4.3 Line speed distribution

Straight lines from the top of the well to the model boundary along the x-, y-, and z-axis directions were made to accurately study the seepage characteristics of methane in each direction under four types of well conditions. Line 1 is the line segment along the x-axis when z = 50 m, line 2 is the line segment along the y-axis when z = 50 m, and line 3 is the well edge from the wellhead to the bottom. The methane seepage velocity on each line was extracted for analysis. The distances from the points on lines 1, 2, and 3 to the wellhead were defined as L_1, L_2, and L_3, respectively.

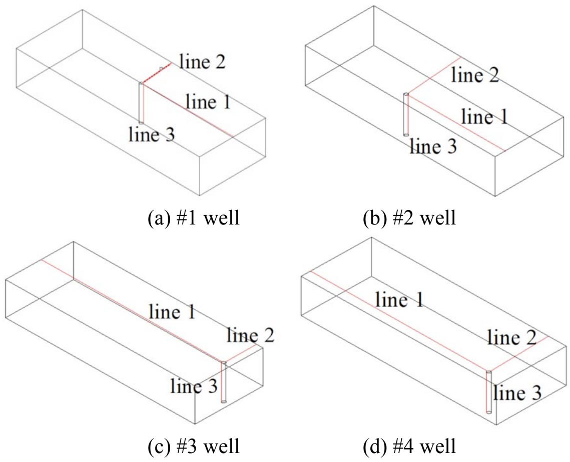
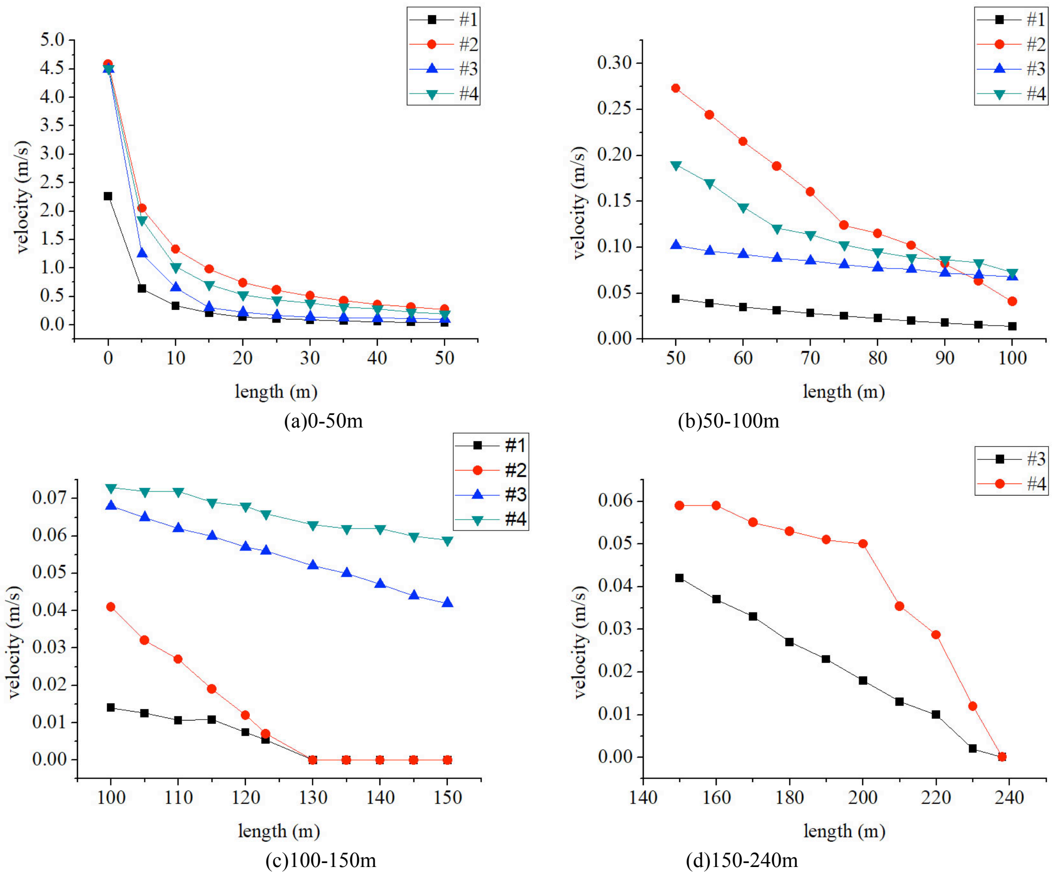


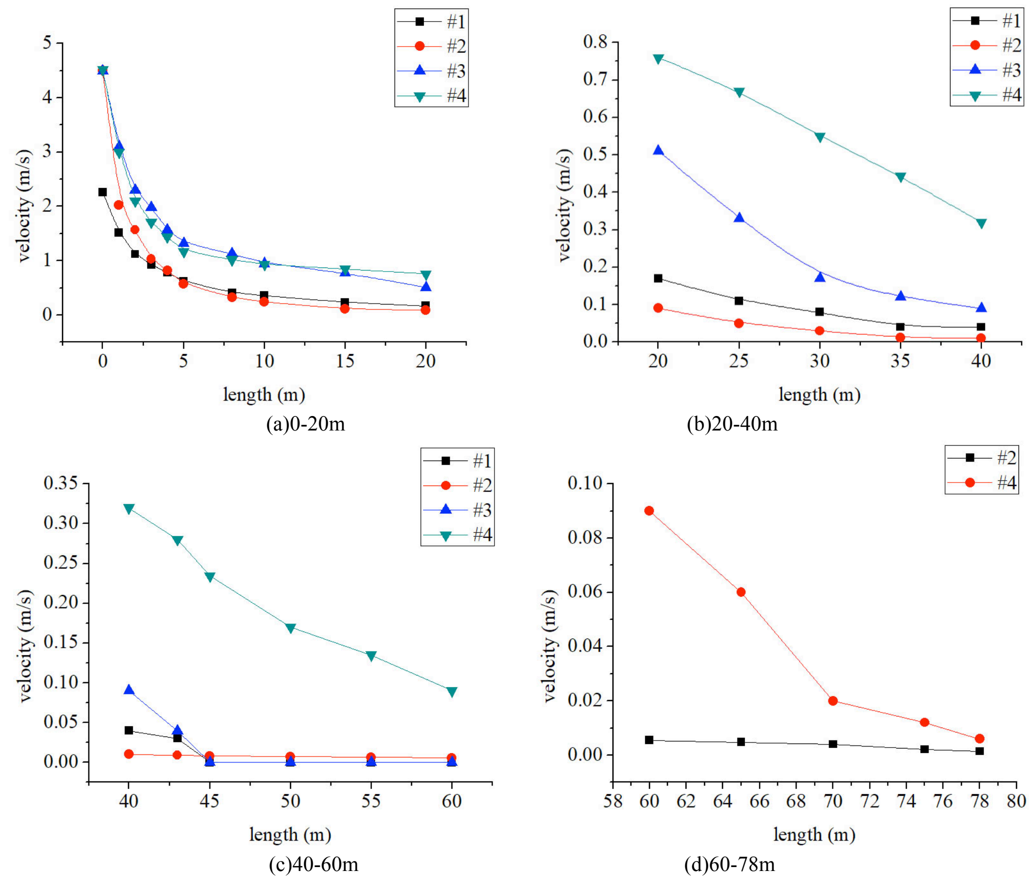
Fig. 8. Schematic of the speed measuring lines



(a)0-50m (b)50-100m

(c)100-150m (d)150-240m

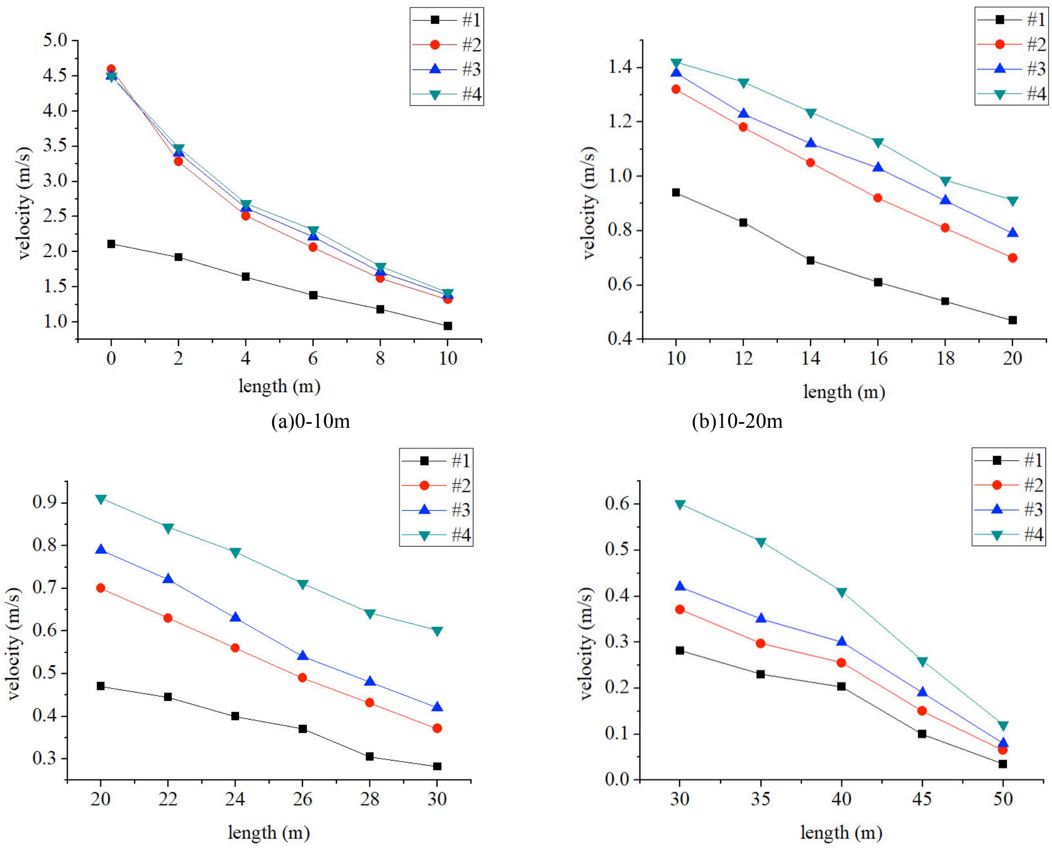
Fig. 9. Methane seepage velocity distribution along line 1



(a)0-20m (b)20-40m

(c)40-60m (d)60-78m

Fig. 10. Methane seepage velocity distribution along line 2



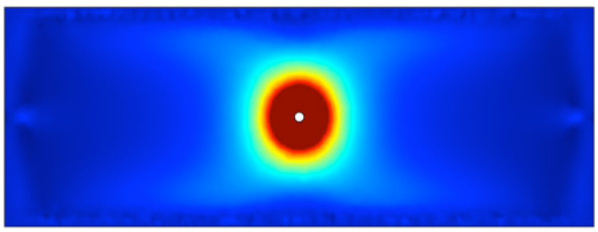
(a)0-10m (b)10-20m
(c)20-30m (d)30-50m

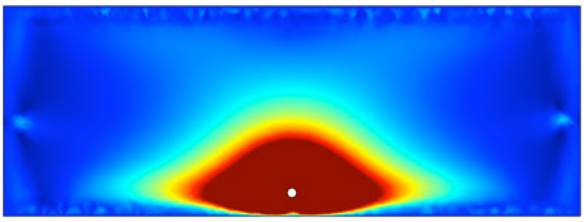
Fig. 11. Methane seepage velocity distribution along line 3

Figure 9 shows the distribution of methane velocity along line 1 under four surface vertical well conditions. In the trending direction, the well arrangement with the seepage velocity of the goaf from big to small is #2, #4, #3, and #1. The gradient of curves under #2 and #4 wells is larger than those under #1 and #3 wells because the lines of the former are in the high-permeability zone of the goaf. When $0 \le L_1 \le 35$ m, the methane seepage velocity v_1 decreases inversely with the increase of L_1. When $L_1 \ge 35$ m, v_1 decreases linearly with a fixed slope as with the increase of L_1 until the model boundary.

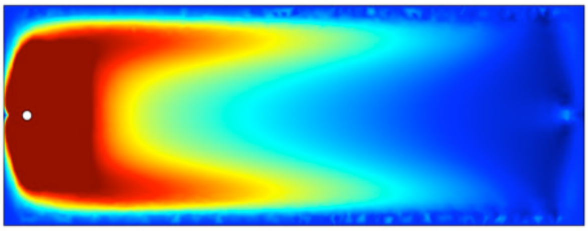
Figure 10 shows the distribution of methane velocity along line 2 under four surface vertical well conditions. In the inclination direction, when $L_2 \le 4$ m, methane seepage velocity in the goaf under #1 well is the lowest among the four wells. When $L_2 \ge 4$ m, the methane seepage velocity of #1 well is higher than that of #2 well. A large amount of methane is transported to the wellbore along the inclination direction of the well because of the flat X-shaped distribution of the high-velocity methane flow area under #1 well condition. However, under #2 well condition, when the methane enters the well in the inclination direction, it needs to pass through the compaction area with low permeability in the middle goaf. The resistance to methane flow in that area is high. When $0 \le L_2 \le 15$ m, the methane seepage velocity v_2 decreases inversely proportional to the increase of L_2. When $L_2 \ge 15$ m, v_2 decreases linearly with L_2 until the model boundary.

Figure 11 shows the distribution of methane velocity along line 3 under four well conditions. In the vertical direction, the methane seepage velocity v_3 shows three distinct stages with the increase of L_3. When $0 \le L_3 \le 5$ m, the methane seepage speed v_3 decreases linearly with a relatively large slope. When $5 \le L_3 \le 40$ m, the methane seepage velocity v_3 slowly decreases linearly. When $40 \le L_3 \le 50$ m, v_3 rapidly and linearly decreases with a large slope. The seepage resistance of methane at the bottom area (0–10 m) of the goaf is large, the seepage velocity is small, and the control effect of surface vertical well on the bottom of the goaf is faint. The seepage velocities of methane under the #2, #3, and #4 wells are higher than that under #1. This difference is the greatest at the top of the goaf and the least at the bottom of the goaf. Methane seepage velocity at the bottom of the goaf trends from #4, #3, #2, to #1 in descending order. The methane velocity at the bottom of the goaf still reaches 0.12 m/s under the #4 well condition because this well position is located at the intersection of the two edges of the high-permeability zone at the edge of the goaf. The surface vertical well has good drainage effect on the goaf in both two directions.

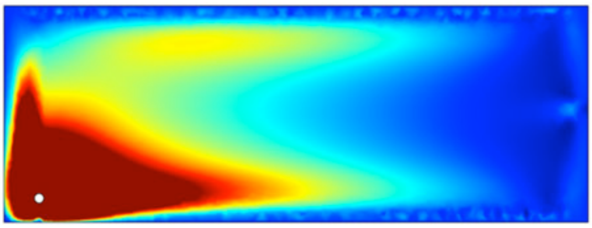

(a) #1 well



(b) #2 well



(c)#3 well



(d) #4 well

Fig. 12. Distribution of high-speed methane flow zone

Figure 12 shows the high-speed methane flow zone in the abandoned mine goaf. The high-speed methane flow zone under #1 well condition is distributed in an “O–X” shape along the well. The high-speed flow zone under #2 well condition exhibits a leaf shape. The high-velocity methane flow areas under the #3 and #4 well conditions are in the high-permeability zone of the goaf and present “C” and “L” shapes, respectively. From the aspect of area, the range of high-speed flow area is the smallest under the #1 well condition. This result is attributed to the well being positioned in the re-compacted area in the middle of the goaf, as well as to the low permeability of coal and rock around the well. The #2, #3, and #4 wells are in the high-permeability zone on the edge of the goaf, and the resistance to methane flow during extraction is small. Therefore, the high-speed methane flow zone is large.

The #4 well is the most ideal location because of its good control over the bottom of the goaf, which has a strong resistance to methane flow. The #2 and #3 wells perform well on one side of the goaf. The effect of drainage under the #1 well condition is the worst. A definite “blind area” for drainage exists under the drainage of each well. The location of the blind area is denoted by the blue and black parts in Fig. 12. Increasing the amount of surface vertical wells is necessary to eliminate the blind area for drainage.

5. Conclusions

This study established the methane seepage model of abandoned mine goafs to determine the reasonable surface vertical well location in abandoned mine goafs. The well locations studied include central position of goaf, middle of the boundary in the trending direction of goaf, middle of the boundary in the inclination direction of goaf, and corner position of goaf. The characteristics of methane seepage under 3D, 2D, and 1D flow fields were analyzed, and the shape and range of high-speed methane flow zones were divided. The following conclusions could be drawn:

(1) Surface vertical wells at the high-permeability zone at the edge of the goaf perform better than that at the center of the goaf. The rate of change of methane velocity at the lines located in the high-permeability zone is lower than that of the other lines in the same direction. Arranging the well in the high-permeability zone at the edge of the goaf can significantly increase the methane extraction speed. Hence, corner position of goaf is the most suitable area for surface vertical well.

(2) The shape of the high-speed flow zone is transformed from a circular shape to that of the high-permeability zone from the top to the bottom of the goaf. The closer to the bottom of the goaf, the closer the high-velocity zone of methane seepage is to the shape of the high-permeability zone in the goaf. The surface vertical well location and the spatial distribution of permeability are the dominant factors affecting the shape and scope of the high-speed flow zone in the upper and lower parts of the goaf, respectively.

(3) Under drainage negative pressure conditions, the methane seepage velocity in the horizontal direction is initially inversely proportional to the distance from the well and then exhibits a negative linear correlation. A three-stage linear downward trend of “fast–slow–fast” is presented from top to bottom in the vertical direction. This trend shows the large resistance of methane seepage at the bottom of the goaf.

(4) The goaf under four surface vertical well conditions have different sizes of blind areas for drainage. Therefore, the effect of single-well on the goaf is limited.

The methane seepage model of abandoned mine goafs established in this study intuitively reflects the effect of surface vertical well with different well locations on the methane drainage effect of goaf. The model has a specific guiding role in the rational arrangement of surface vertical well. However, the factors affecting the methane production of surface vertical well are not limited to the well position. The influence of other factors such as negative pressure and final hole position on the methane drainage effect has yet to be further studied.

Acknowledgements
The study was supported by the National Science Fund for Excellent Young Scholars (No.51422404), The National Natural Science Foundation of China (No.51574172) and the Key Scientific and Technological Coal Projects of Shanxi Province (MQ2014-12).

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