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Research Article

Research on Gas Extraction Technology of Directional Long Borehole in Ultrathick Coal Seam

Yaobin Li,[1,2] **Tao Jiang**,[2] **and Xin Guo**[2]

[1]*Joint National-Local Engineering Research Center for Safe and Precise Coal Mining, AnHui University of Science and Technology, Huainan, 232001 Anhui, China*
[2]*School of Safety Science and Engineering, Anhui University of Science and Technology, Huainan, 232001 Anhui, China*

Correspondence should be addressed to Tao Jiang; jt980804@163.com

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Gas extraction is an important way to control gas disasters. The effect of traditional gas extraction drilling on ultrathick coal seam is not well. In order to improve the rate of gas extraction, directional long drilling is used to replace conventional drilling for coal seam gas extraction. Through the combination of numerical simulation and field experimentation, the stress distribution around borehole is analyzed, and the influence of different time, different gas pressure, different negative pressure of extraction, and different permeability of coal body on directional borehole is simulated. According to the experimentation of Baode Mine, the data of gas drainage volume of conventional directional drilling are recorded and analyzed. The results indicate that the directional drilling is more suitable for Baode Mine 81306 working face of coal seam 8 gas extraction operation. Directional drilling is better than conventional drilling in work, with good drainage stability and large gas drainage volume, which can greatly reduce the outburst time and improve the gas drainage rate.

1. Introduction

According to data from the Ministry of Ecology and Environment of China, from 2010 to 2020, the proportion of coal consumption in China's primary energy consumption structure decreased from 69.2% to 56.8%. Although the proportion of coal consumption in China has decreased, coal still occupies a dominant position in China's primary energy consumption [1–3]. Even under the goal of low-carbon economy, China's demand for coal resources is still very large. Therefore, in a long period of time in the future, the importance of coal resources to China's economic development is self-evident [4, 5]. However, the geological conditions of coal seam occurrence in China are very complicated, and the permeability of coal seam is low, which leads to the emergence of many risk factors in the process of coal mining, among which the gas disaster is the most serious. The total number of coal and gas outburst events in China accounts for more than one-third of the total number of coal and gas outburst events in the world. Therefore, the elimination of a series of gas accidents such as coal mine gas explosion and gas outburst is an important issue in coal mine safety production at present [6–13]. Currently, gas extraction in coal mine is the main method to solve gas outburst, gas explosion, and other gas disasters. It has important significance for the development of coal industry to study coal mine gas drainage, improve existing gas drainage through borehole design, optimize borehole parameters, improve coal mine gas drainage rate, and reduce gas accidents [14–17].

At present, many studies have been carried out by researchers on gas extraction. Shi studied and analyzed the existing problems of gas treatment in recent years and solved the gas treatment problem of thick coal seam tunneling face by introducing the directional long drilling extraction process along the layer to preextract thick coal seam [18, 19]; Wang and Ma used directional long drilling holes in the roof to control the gas instead of high drainage roadway and proposed the coal gas drainage technology of "hole instead of roadway," which reduced the workload and the cost of gas drainage [20]; Zhang designed a directional long borehole predrainage roadway strip, which greatly reduced the time of gas extinction, and achieved good drainage effect [21, 22]; Wang conducted numerical simulation on directional long borehole of gas extraction in medium and hard coal seam, analyzed the influence degree of drilling length and spacing on gas extraction by drilling hole, and provided reference for the analysis of other influencing factors of gas extraction drilling [23–25]; Chen and Luo used long boreholes in bedding to prepump working face and transport pipeline, which saved the time of eliminating outburst and completed the technological innovation experiment project of "one borehole and two eliminating" in long drilling holes in bedding [26]; Zhang et al. studied the directional long drilling equipment at domestic and abroad, found out the problems existing in the application of RIGS drilling abroad under the geological conditions of coal seams in China, and put forward the corresponding opinions on optimization of compatibility [27].

However, most researches are aimed at the optimization of drilling design, and the research on the influencing factors of directional drilling is not sufficient. In view of this, this paper uses the method of combining numerical simulation and field measurement to analyze the influence of different factors on directional drilling and optimize the extraction process. Through the analysis of directional drilling and conventional drilling gas drainage CaiLiang, the advantages and disadvantages of the two kinds of drilling are analyzed, and the accuracy of the simulation is further verified. It is of great significance to further analyze the influence factors of directional drilling technology and also provides the basis for the design and optimization of directional drilling in Baode Mine.

2. Project Profile

The location of this test is the main air withdrawal channel of Baode Mine working face 81306, return air passage 81306, and glue transport passage 81306 of No. 8 coal seam of Baode Coal Mine. No. 8 coal seam is located above S3 sandstone at the bottom of Shanxi Formation (P1S). The coal seam is a gas coal with medium ash, high volatile content, low sulfur content, medium and high calorific value, good thermal stability, rich oil, and high ash content. Coal thickness is 2.15~10.50 m, with an average of 7.36 m; the thickness of pure coal is 3.19~8.84 m with an average of 6.01 m and with medium to extrathick coal seam, mainly thick coal seam. The structure of the coal seam is complex, including 0~8 layers of gangue, usually 3~4 layers, and the total thickness of gangue is 0.3~2.6 m, with an average thickness of 1.06 m. The roof is sandy mudstone or mudstone, part of which is coarse-grained sandstone; the bottom plate is mainly mudstone and secondary siltstone. There are 58 coal spots in the whole area, and all the coal thickness is recoverable. The mining index of coal seam is 1, and the coefficient of variation is 33%, which is a stable and recoverable coal seam in the whole area. The thickness of the coal seam is generally thick in the west and thin in the east, thick in the middle, and thin on both sides. The old coal seam is mostly coarse, medium, and fine grained sandstone with a thickness of 5~20 m and an average of 12.67 m. Most of the immediate roof is developed, the lithology is sandy mudstone, siltstone, mudstone, and thin sandstone, and the thickness is 0~16.13 m. It is mudstone and carbonaceous mudstone with thickness less than 0.5 m.

3. Stress Distribution and Gas Occurrence around Borehole

3.1. Borehole Stress Distribution. In the drilling process, the stress distance around the drilling hole is different from the drilling position, and there are broken zones and plastic zones. The borehole may collapse after stress change. In order to prevent the drilling collapse and deformation, it is necessary to explore the stress distribution around the drilling hole. As the drilling goes deeper, the buried depth of coal seam changes, the pressure changes, and the coal body change from elastic deformation to plastic deformation. When the drilling is finished, the stress distribution will keep balance again. If the initial gas pressure is greater than the surrounding rock mass, the coal body is in an elastic state; otherwise, the coal body becomes an elastic-plastic state [28, 29]. Assuming that the surrounding rock of the borehole is a continuous, homogeneous, and isotropic completely linear elastic body, any section of the borehole is taken for study:

3.1.1. Balance Equation.

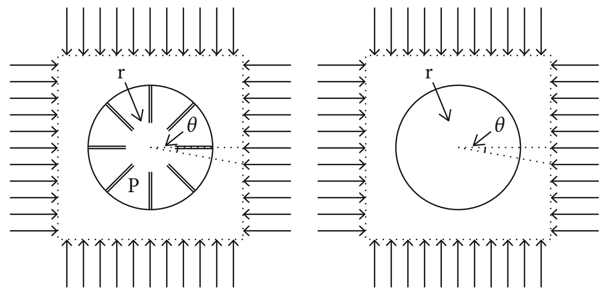
$$\begin{aligned} \frac{\partial \sigma_\rho}{\partial \rho} + \frac{1}{\rho}\frac{\partial \tau_{\rho\theta}}{\partial_\theta} + \frac{\sigma_\rho - \sigma_\theta}{\rho} + f_\rho = 0, \\ \frac{\partial \tau_{\rho\theta}}{\partial \rho} + \frac{1}{\rho}\frac{\partial \sigma_\theta}{\partial_\theta} + \frac{2\tau_{\rho\theta}}{\rho} + f_\rho = 0, \end{aligned} \tag{1}$$

where σ_ρ is the radial normal stress; σ_θ is the annular normal stress; $\tau_{\rho\theta}$ is the shear stress; ρ is the radial coordinates; θ is the toroidal coordinates; f_ρ is the radial force component; and f_θ is the circumferential force component.

3.1.2. Geometric Equations.

$$\begin{aligned} \varepsilon_\rho &= \frac{\partial u_\rho}{\partial \rho}, \\ \varepsilon_\theta &= \frac{u_\rho}{\rho} + \frac{1}{\rho}\frac{\partial u_\theta}{\partial \theta}, \\ \gamma_{\rho\theta} &= \frac{1}{\rho}\frac{\partial u_\rho}{\partial \theta} + \frac{\partial u_\theta}{\partial \rho} - \frac{u_\theta}{\rho}, \end{aligned} \tag{2}$$

where ε_ρ is the radial linear strain; ε_θ is the circumferential linear strain; $\gamma_{\rho\theta}$ is the tangential strain; u_ρ is the radial displacement; and u_θ is the circumferential displacement.



(a) (b)

Figure 1: Stress analysis around borehole.

3.1.3. Constitutive Equation.

$$\varepsilon_\rho = \frac{1-\mu^2}{E}\left(\sigma_\rho - \frac{\mu}{1-\mu}\sigma_\theta\right),$$
$$\varepsilon_\theta = \frac{1-\mu^2}{E}\left(\sigma_\theta - \frac{\mu}{1-\mu}\sigma_\rho\right), \quad (3)$$
$$\gamma_{\rho\theta} = \frac{2(1+\mu)}{E}\tau_{\rho\theta},$$

where E is the modulus of elasticity.

According to Saint Venant's Principle, a square boundary can be simplified to a circular boundary, which is regarded as a cylinder under pressure both inside and outside. In Figure 1(a), stress state of drilling hole is

$$\sigma_\rho = -\frac{R^2/\rho^2 - 1}{R^2/r^2 - 1}P - \frac{1 - r^2/\rho^2}{1 - r^2/R^2}\cdot\frac{\lambda+1}{2}\sigma_z,$$
$$\sigma_\theta = \frac{R^2/\rho^2 + 1}{R^2/r^2 - 1}P - \frac{1 + r^2/\rho^2}{1 - r^2/R^2}\cdot\frac{\lambda+1}{2}\sigma_z, \quad (4)$$
$$\tau_{\rho\theta} = 0,$$

where R is the radius of the cylinder.

Also according to Saint Venant's Principle, square boundary is simplified to circular boundary, and the stress state of Figure 1(b) is obtained by semi-inverse solution:

$$\sigma_\rho = -\frac{\lambda-1}{2}\sigma_z\left(1 + \frac{3r^4}{\rho^4} - \frac{4r^2}{\rho^2}\right)\cos 2\theta,$$
$$\sigma_\theta = \frac{\lambda-1}{2}\sigma_z\left(1 + \frac{3r^4}{\rho^4}\right)\cos 2\theta, \quad (5)$$
$$\tau_{\rho\theta} = \frac{\lambda-1}{2}\sigma_z\left(1 + \frac{2r^2}{\rho^2} - \frac{3r^4}{\rho^4}\right)\sin 2\theta.$$

The total stress state of drilling hole is

$$\sigma_\rho = -\frac{\left(R^2/\rho^2\right) - 1}{\left(R^2/r^2\right) - 1}P - \frac{1 - \left(r^2/\rho^2\right)}{1 - \left(r^2/R^2\right)}\cdot\frac{\lambda+1}{2}\sigma_z - \frac{\lambda-1}{2}\sigma_z\left(1 + \frac{3r^4}{\rho^4} - \frac{4r^2}{\rho^2}\right)\cos 2\theta,$$

$$\sigma_\theta = \frac{\left(R^2/\rho^2\right) + 1}{\left(R^2/r^2\right) - 1}P - \frac{1 + \left(r^2/\rho^2\right)}{1 - \left(r^2/R^2\right)}\cdot\frac{\lambda+1}{2}\sigma_z + \frac{\lambda-1}{2}\sigma_z\left(1 + \frac{3r^4}{\rho^4}\right)\cos 2\theta,$$

$$\tau_{\rho\theta} = \frac{\lambda-1}{2}\sigma_z\left(1 + \frac{2r^2}{\rho^2} - \frac{3r^4}{\rho^4}\right)\sin 2\theta. \quad (6)$$

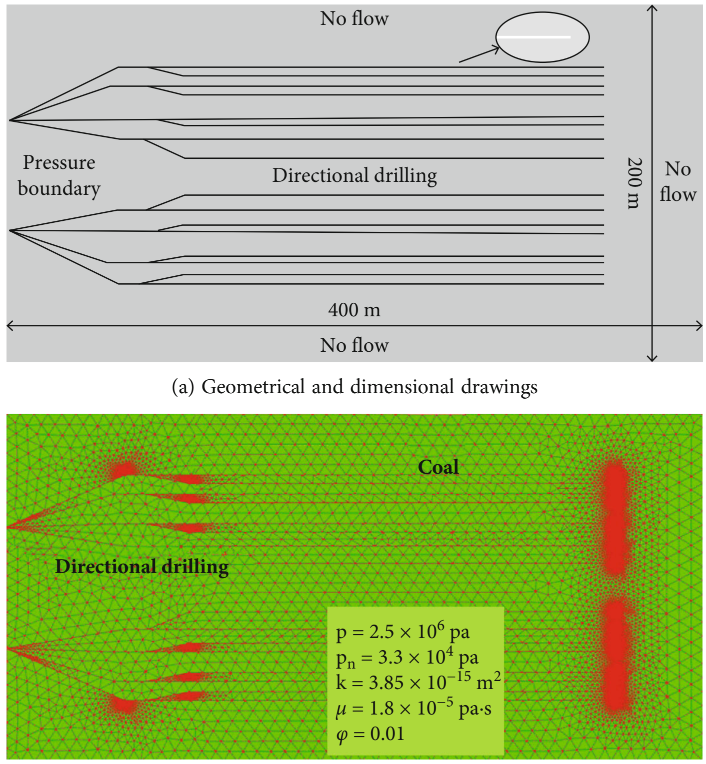
The stress state at the hole wall $(\rho = R)$ is

$$\sigma_r = -P,$$
$$\sigma_\theta = \frac{R^2/r^2 + 1}{R^2/r^2 - 1}P - \frac{\lambda+1}{1 - \left(r^2/R^2\right)}\cdot\sigma_z + 2(\lambda-1)\sigma_z\cos 2\theta,$$
$$\tau_{r\theta} = 0. \quad (7)$$

3.2. Gas Occurrence State. In addition, the occurrence state of coal seam gas mainly includes adsorption and dissociation, which exist in a dynamic adsorption-desorption equilibrium state. The adsorbed gas generally accounts for 80%–90% of the total coal seam gas. Because the effective area of directional drilling on coal seam is large, the original stress distribution of coal body can be changed in a large range, and the dynamic equilibrium of adsorption and desorption can be broken, so that the gas is transformed from adsorption state to free state. After the coal body is drilled under the combined action of stress, gas pressure, and negative pressure, the free gas continues to flow into the borehole under the action of pressure gradient. The coal gas is effectively extracted and extracted, and the coal body shrinks and deforms. The permeability of the coal body increases, and the stress and gas pressure decrease. The influence radius of the gas extraction in the directional long borehole expands, and the gas extraction effect is significantly improved, so as to realize the large-scale effective extraction of coal seam gas [30].

4. Numerical Simulation

In order to further study the influencing factors of directional drilling in the working face 81306 of Baode Mine, combined with the geological conditions of the working face,



(a) Geometrical and dimensional drawings

(b) Grid drawing

Figure 2: Geometric diagram and grid diagram of gas extraction model in directional borehole.

a numerical model was established by COMSOL software to analyze the influence of different factors on directional drilling. The geometric model of gas extraction by directional drilling is shown in Figure 2(a), and the simulation grid is shown in Figure 2(b). The length and width of the model are 400 m × 200 m. The gas pressure of coal body is 2.5 Mpa, the negative pressure of extraction is 33 KPa, and the permeability is 3.85 mD. The simulation object is two groups of directional drilling holes, each group of drilling end consists of 8 branch holes, and the length of sealing hole section is 8 m. This model is used to study the effects of extraction time, gas pressure, negative pressure of extraction, and permeability of coal body on the extraction effect.

4.1. Different Extraction Time. Figure 3 shows the change of gas pressure in borehole after 10 d, 100 d, 200 d, 400 d, 600 d, and 800 d of drainage. It can be seen from the figure that in the initial stage of drainage, the influence radius of borehole is small, and the gas pressure around borehole basically maintains at about 2.5 Mpa. With the continuous pumping, the influence radius increases and the pressure value decreases. At the same time, the decrease of gas pressure in the early stage is larger than that in the later stage. After about 800 days of continuous pumping, the intermediate area between the two boreholes was effectively pumped. However, as shown in Figure 4, there are weak areas of extraction at the corner of the borehole and between the two boreholes with large spacing. These areas should be eliminated by increasing the extraction time or improving the borehole design to achieve effective extraction of all coal bodies.

4.2. Different Gas Pressure. The coal extraction process under three gas pressures (1.5 MPa, 2.5 MPa, and 3.5 MPa) was simulated and analyzed. Figure 5 shows the gas pressure changes on the pressure monitoring line under three different original pressures. It can be seen that on the one hand, the gas pressure around the borehole continues to decline with the progress of extraction. On the other hand, when the coal gas pressure is 1.5 Mpa, after a period of extraction, the area with pressure less than 0.74 Mpa around the borehole is the largest, followed by 2.5 Mpa coal body and 3.5 Mpa coal body. When the gas pressure of coal extraction is 1.5 Mpa after 400 days, most pressure values around the borehole are less than 0.74 MPa and after 800 days are less than 0.74 MPa. When the coal gas pressure is 2.5 Mpa, most of the pressure around the borehole is less than 0.74 Mpa after 800 days of extraction except for the most middle position of the monitoring line. When the gas pressure of coal body is 3.5 Mpa, after 800 days of extraction, the area with gas pressure less than 0.74 Mpa around the borehole is less than 2.5 Mpa. The above analysis shows that the higher the gas pressure of coal body, the longer the time required for extraction to reach the standard. When the gas pressure is high, it is suggested to take permeability enhancement measures to improve the permeability of coal body and shorten the extraction time.

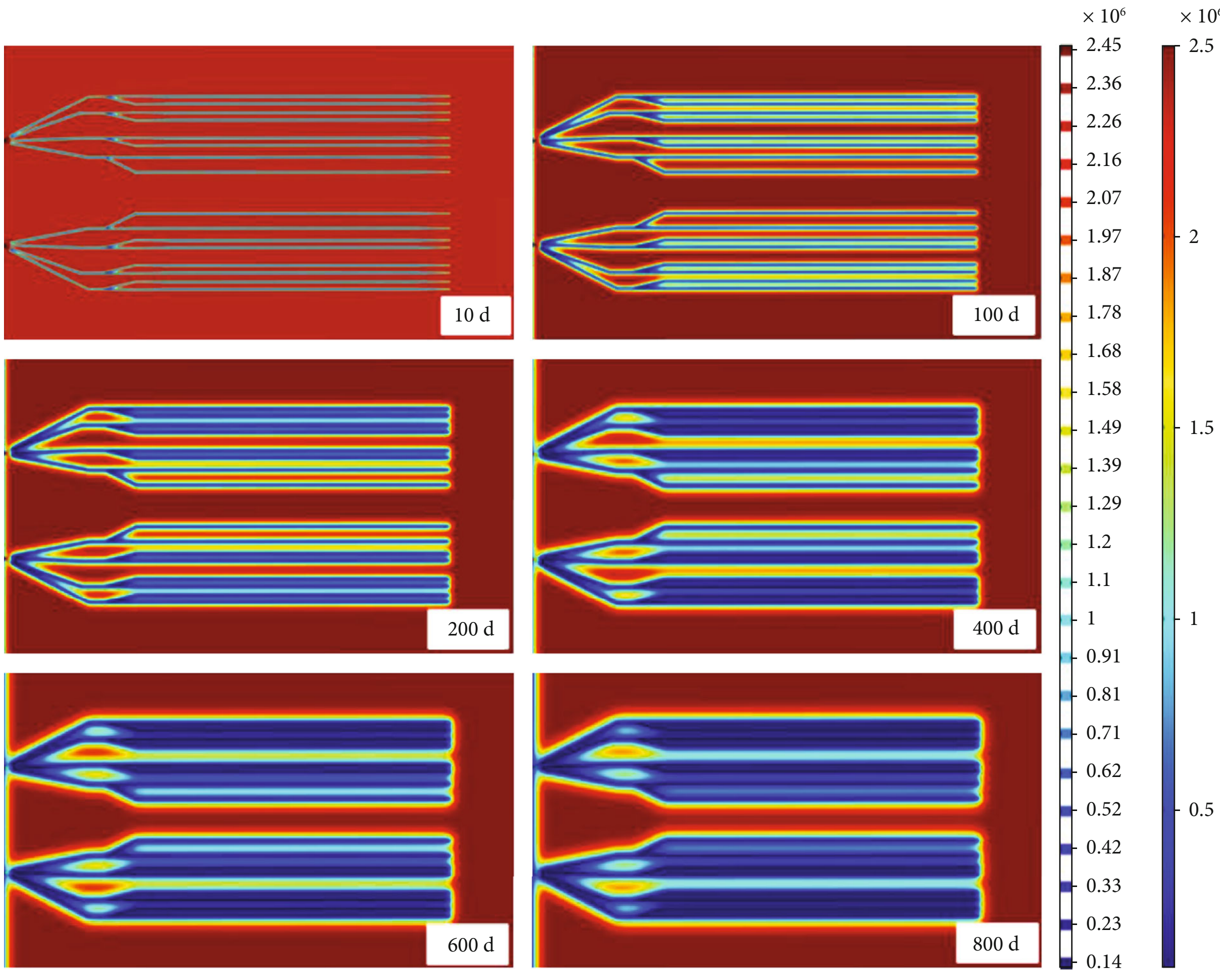


Figure 3: Borehole gas pressure variation under different extraction time.

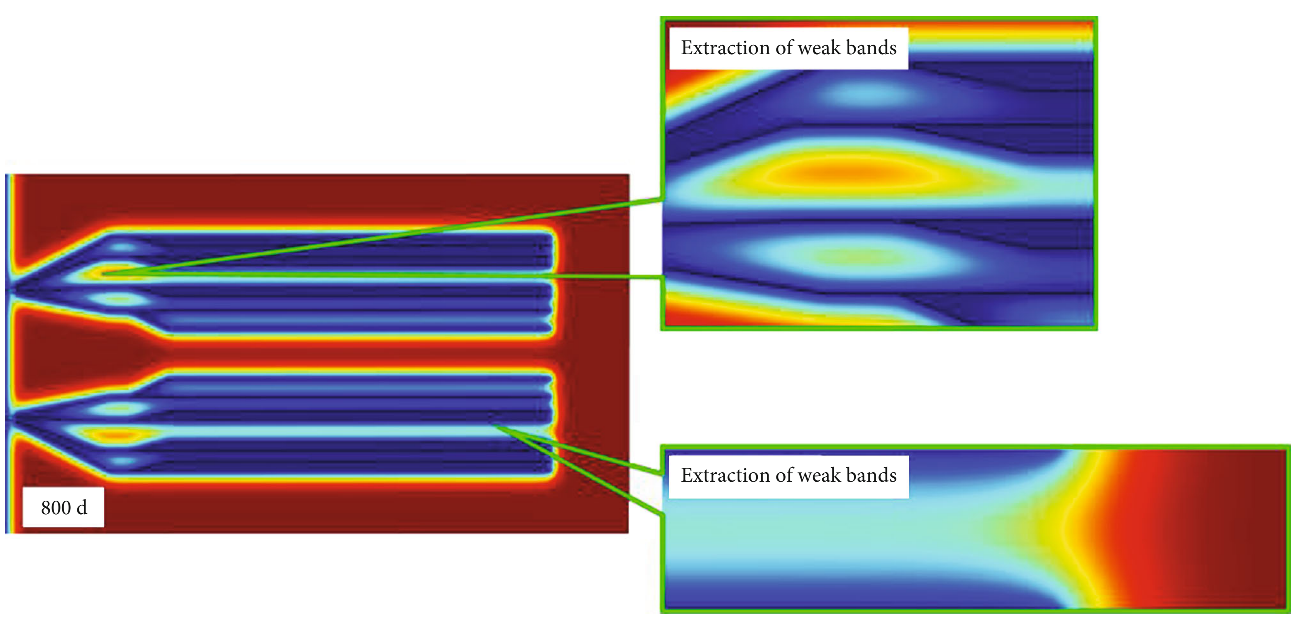


Figure 4: Weak zone of directional drilling extraction.

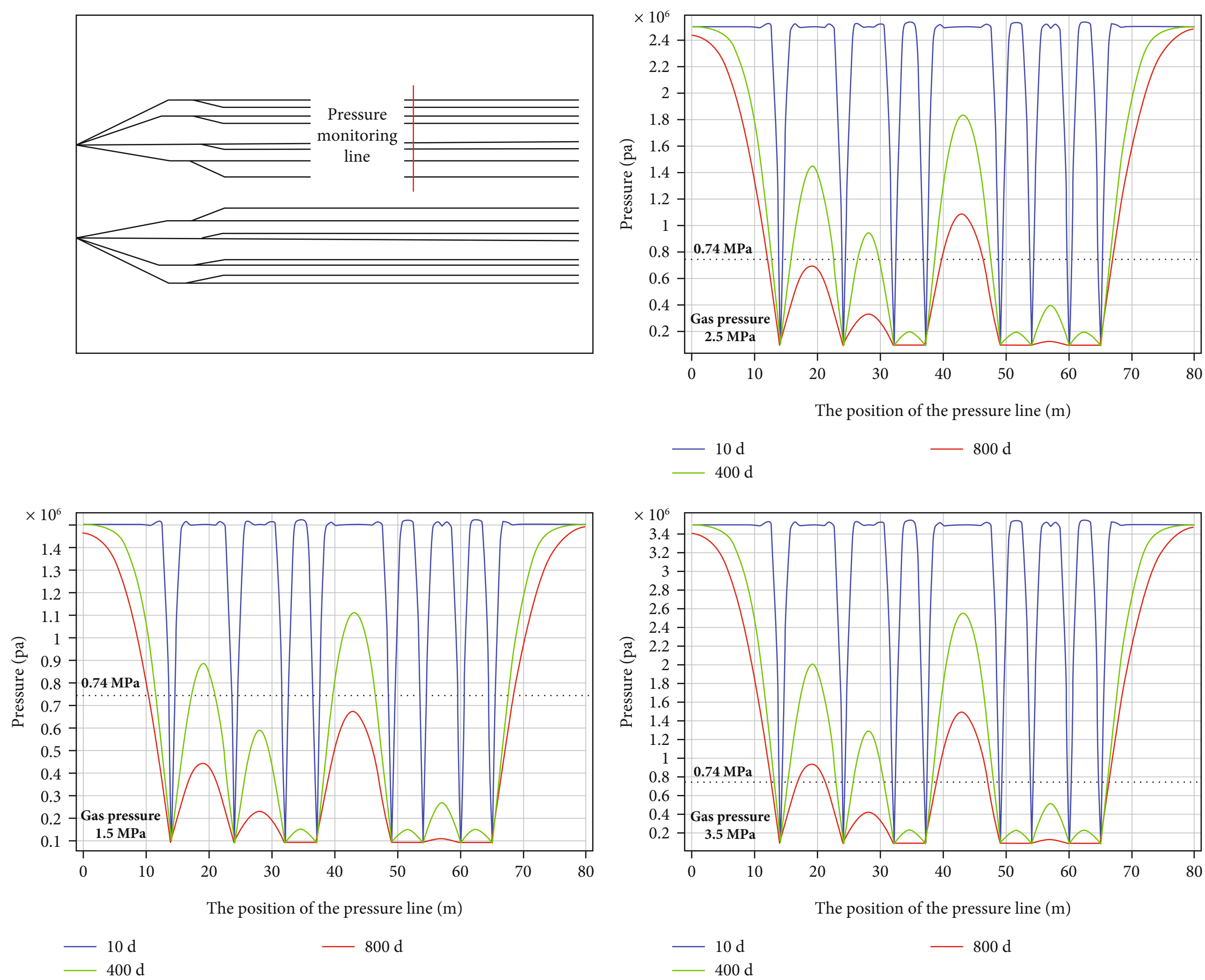


Figure 5: Comparison of extraction effects under different original gas pressures.

4.3. Different Suction Negative Pressure. At present, the negative pressure of drainage used in directional drilling in Baode Mine is about 33 KPa, and 13 KPa, 23 KPa, and 43 KPa are selected for comparative analysis. Figure 6 shows the gas pressure changes under different negative pressure conditions after 400 days of drainage. It can be seen that the increase of the negative pressure of drainage will make the gas pressure around the borehole decrease greatly. However, the above effects are limited, mainly because of the low permeability of coal seam itself. According to Darcy's Law, although the greater the negative pressure of extraction, the greater the differential pressure power of gas flow, the low permeability limits the positive effect of the increase of differential pressure on gas flow. At the same time, if the negative pressure value is too large, it will aggravate the degree of air leakage in the borehole sealing section and reduce the concentration and efficiency of gas extraction. So there is no need to increase the suction negative pressure excessively.

4.4. Different Coal Permeability. The gas extraction process of directional drilling was analyzed under three different coal permeability (0.385 mD, 3.85 mD, and 38.5 mD). Figure 7 shows the gas pressure changes after 100, 200, 400 and 800 days of extraction. It can be seen that the reduction range and degree of gas pressure around the borehole are positively correlated with the permeability value. When the permeability is 0.385 mD, the influence range of drainage is the smallest. Until 800 days after drainage, the drainage standard is still not achieved. However, when the permeability is 38.5 mD, the gas around the borehole decreased greatly, and the gas pressure decreases rapidly during the whole extraction process. After 800 days, the extraction standard is basically achieved, and the area of weak extraction area also drops to the lowest value. Therefore, for the coal body with high permeability, the design time of extraction can be appropriately shortened. For the coal body with low permeability, pressure relief and permeability enhancement measures such as hydraulic slit and loose blasting are needed to improve the pumping effect.

5. Field Test

81306 working face extraction boreholes include conventional boreholes and directional boreholes. This experiment

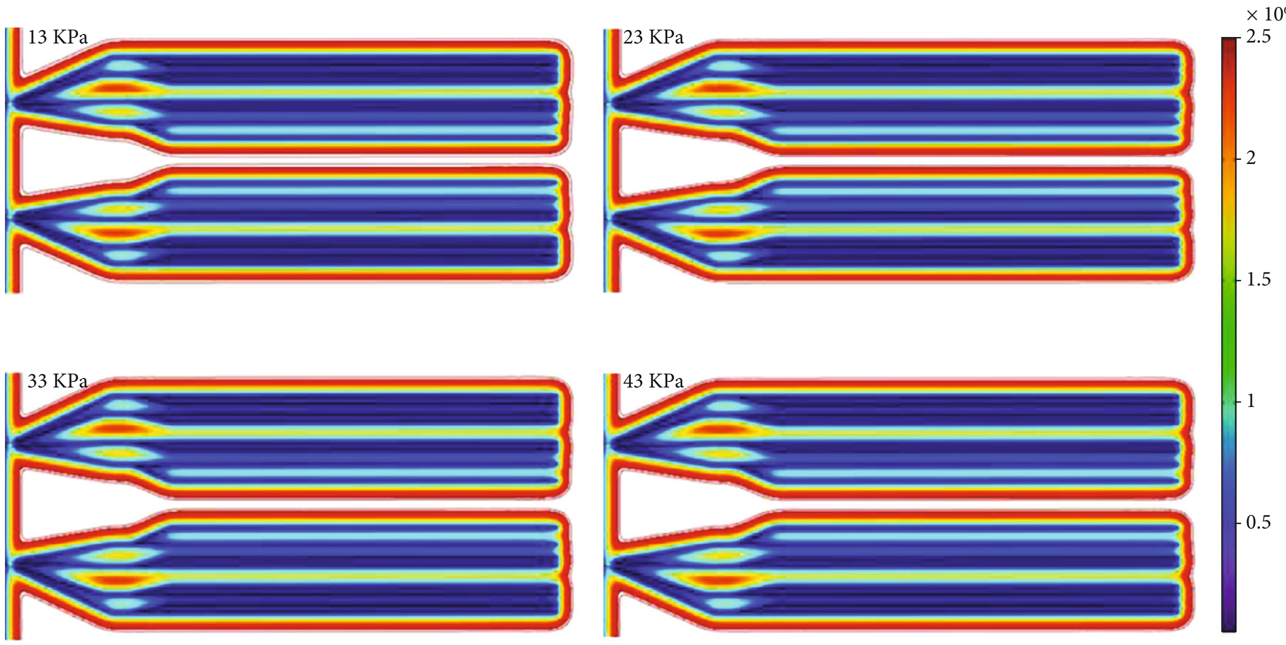


Figure 6: Gas pressure changes under different negative pressures (after 400 d).

mainly focuses on the comparative analysis of the drainage effect of two different hole distribution methods at the working face 81306 of Baode Mine. Figures 8 and 9, respectively, show the gas drainage diagram of directional borehole in the main drainage channel and the gas drainage diagram of conventional borehole in return air passage and glue transport passage. In the main air withdrawal channel, a 1000-meter directional borehole is adopted to extract gas. 81306 return air passage and 81306 glue transport passage are extracted by conventional boreholes. The extraction data of the two boreholes are collected and compared to analyze the advantages and disadvantages of the two boreholes.

A total of 30 months of gas extraction data from April 2011 to October 2013 were collected for analysis. The comparative analysis of the average extraction concentration and the pure extraction amount of the two boreholes is obtained:

5.1. Comparative Analysis of Average Extraction Concentration of Two Boreholes. The gas concentration extracted by directional drilling and conventional drilling in working face 81306 was compared and analyzed by drawing a contrast diagram as follows (Figure 10):

Directional drilling can be seen from the above; the average concentration of extraction in the extraction of gas in this period of time of attenuation is lesser, which can keep better extraction concentration. Even in the late state of extraction, extraction concentration remains at about 50%, while the return air and glue transported by conventional drilling along the through have different degrees of attenuation in the late stage of extraction. The extraction concentration of borehole in the No. 1 return air passage decreases rapidly, and the average extraction concentration in the later period decreases to about 10%. The extraction concentration of borehole in the glue transport passage also decreases significantly. It is found that the directional borehole has a better stability of extraction concentration and can still maintain a better extraction concentration in the later period of gas extraction. Therefore, under the condition of permitting, directional drilling is designed and constructed as much as possible for gas extraction.

5.2. Comparison and Analysis of 100 m Hole Extraction Pure Cumulative Quantity. The extraction effects of the two boreholes were compared through the comparative analysis of the 100-meter cumulative extraction pure amount of directional drilling and conventional drilling. The cumulative extraction purity of 100-meter boreholes in two boreholes is shown in the following (Figure 11):

From the above, we can see clearly that with the increasing number of extraction from drilling time, hundreds of meters drilling accumulative extraction from scalar are also increasing. However, compared with directional drilling and conventional drilling hundreds of meters total extraction from scalar, directional drilling still had better extraction effect. Compared with the conventional drilling, directional drilling has a more stable extraction concentration, Therefore, more pure gas can be extracted.

By preserved Baode Mine 81306 working face of the Lord from directional drilling and return air channel and glue along the trough of normal drilling analysis and comparison, normal drilling extraction concentration is generally lower than the directional drilling; only just started extraction, the draining directional borehole extraction and extraction of normal drilling concentration are higher than that of directional drilling, and conventional drilling attenuated rapidly. With the progress of drainage, the extraction concentration of conventional boreholes has been decreased. Just from the point of extraction concentration, if conditions are available, directional drilling can be used for gas

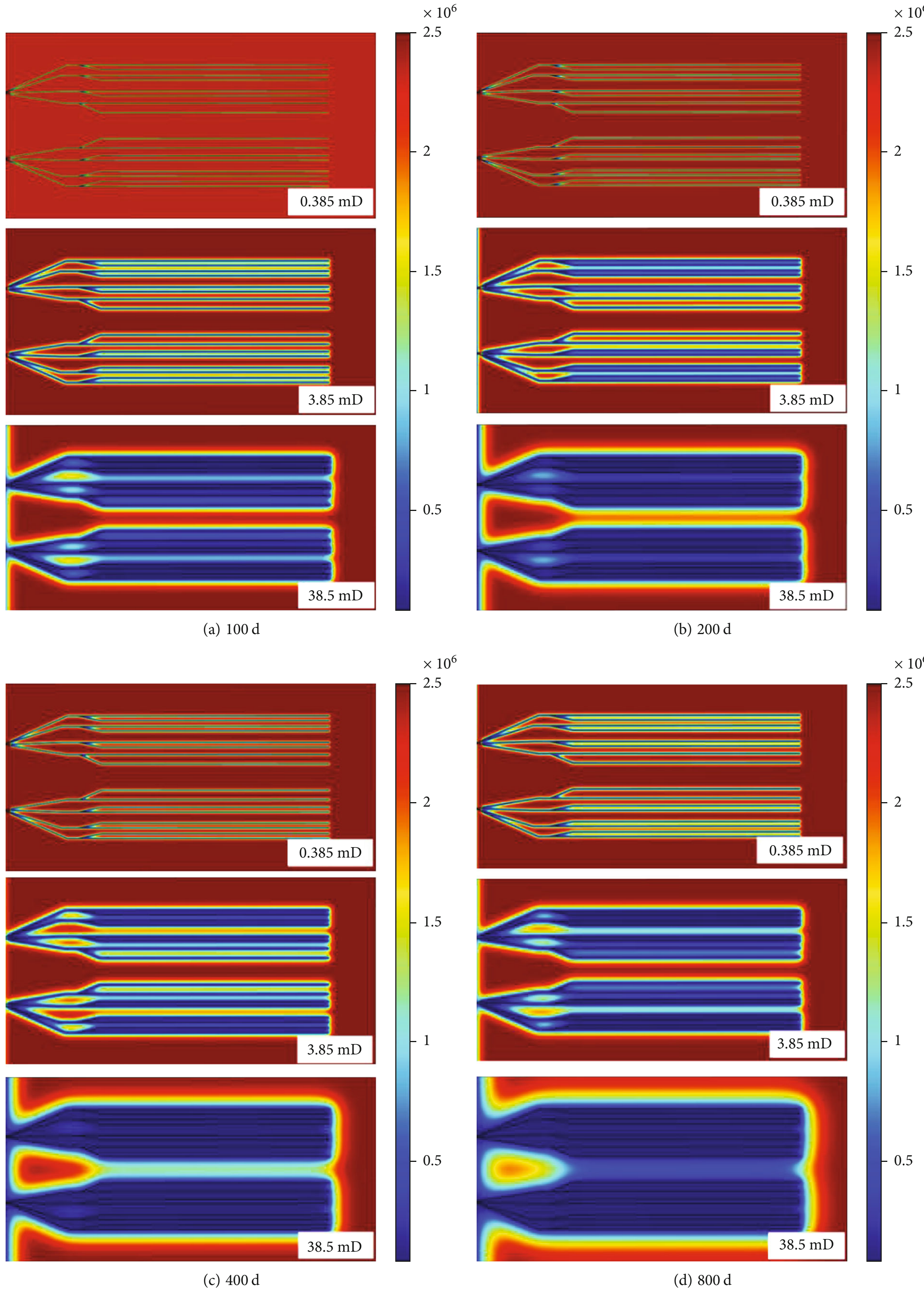


Figure 7: Gas extraction process diagram under different permeability.

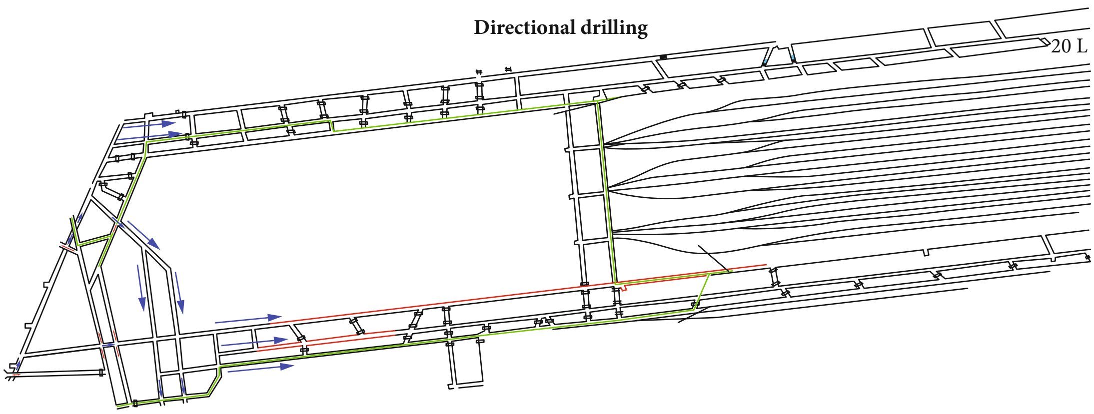


Figure 8: Gas drainage from directional boreholes in the main drainage channel.

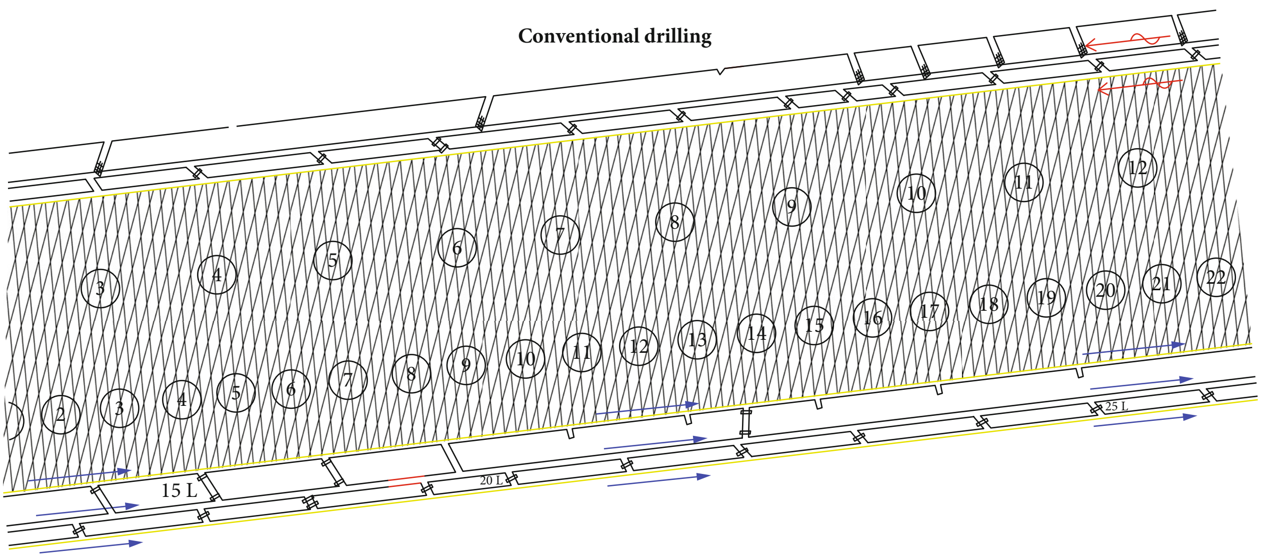


Figure 9: Conventional gas drainage from boreholes in the return air passage and glue transport passage.

preextraction as far as possible, so as to ensure good extraction effect. The reason why the cumulative pumping amount of directional drilling is larger than that of conventional drilling is that directional drilling has a deeper hole sealing depth and better hole sealing effect, which can maintain a good pumping concentration for a long time. At the same time, directional drilling can constantly adjust drilling angle according to the occurrence of coal seam, directional drilling can keep a high proportion of coal detection rate, and branch drilling can also continue to penetrate into the depth of coal seam gas extraction.

Directional drilling is generally superior to the extraction effect of normal drilling, but normal drilling also has its own advantages. Normal drilling rig is small, convenient to move, and easy to operate., The construction time of a drilling is shorter, and the problems of construction are easier to deal with. Some problems are relatively short in hole sealing distance of directional drilling, and the requirements for negative pressure of extraction are smaller. And directional drilling has some defects in these aspects, such as directional drilling, construction requires a relatively large space, drilling operation is more complex than conventional drilling, sealing hole length is generally longer than conventional drilling, and pumping negative pressure is about twice the conventional drilling. Therefore, the best drilling method should be selected according to the actual situation.

6. Conclusion

(1) Through the collection and comparison of field experimental data of 81306 working face, it is found that although directional drilling is more difficult to operate than conventional drilling and requires greater space and cost, directional drilling has better gas extraction stability than conventional drilling. The gas extraction concentration of the conventional boreholes in the return air passage and glue transport passage of the working face 81306 began to decline after 150 days of extraction and sharply decreased to less than 25% after 200 days, while the gas extraction concentration of the directional boreholes continued to increase. At 200 days, the gas

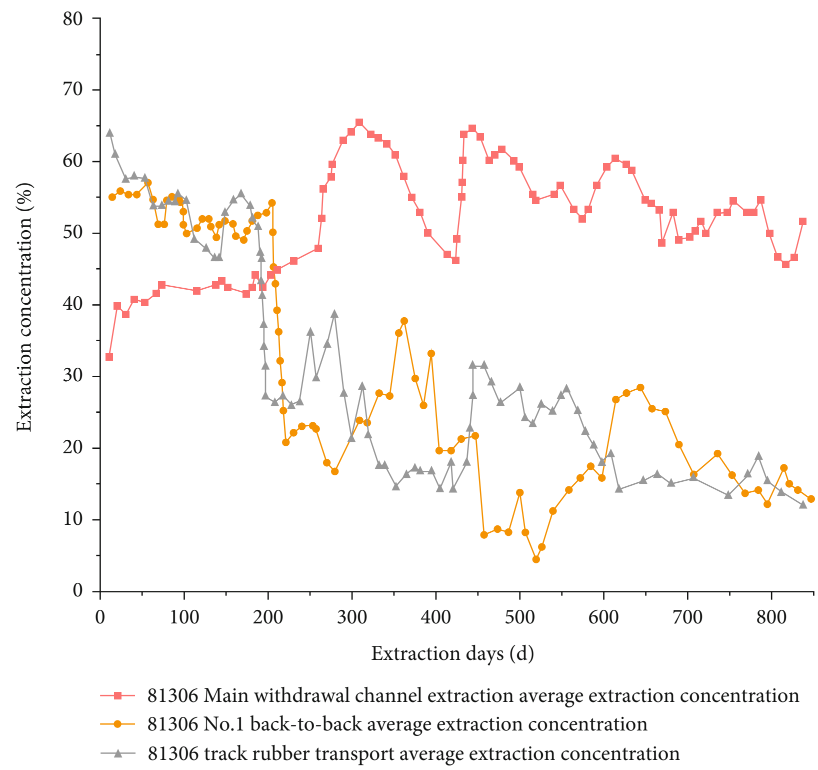


Figure 10: Comparison of extraction concentration between directional drilling and conventional drilling in working face 81306.

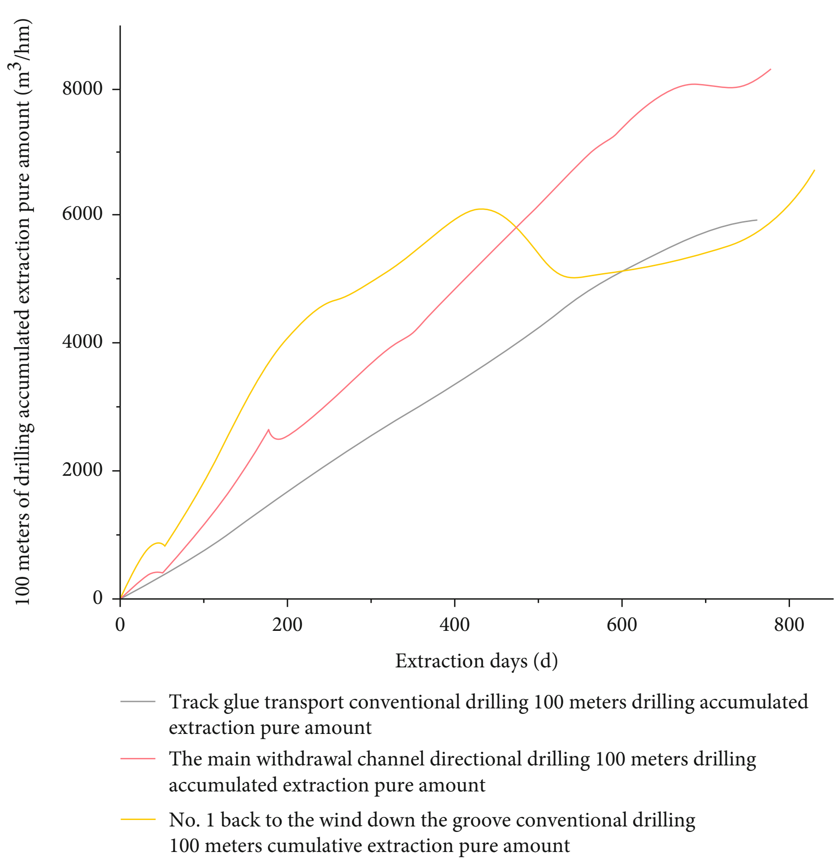


Figure 11: Comparison of cumulative pure extraction volume between directional drilling and conventional drilling on the working face 81306.

extraction concentration of directional drilling is about 44%, and at 350 days, the gas extraction concentration of directional drilling is about 61%. The gas extraction concentration was originally higher than that of conventional drilling in the same period. After 800 days of gas extraction, the gas extraction concentration of conventional drilling has decreased to about 14%, while the gas extraction concentration of directional drilling can still be maintained at about 50%. Compared with conventional drilling, directional drilling has longer service life, less attenuation of gas extraction concentration, higher stability, and better sealing effect. Even in the late stage of extraction, it can still maintain a good extraction concentration, greatly improve the extraction efficiency, and shorten the outburst elimination time. Compared with directional drilling, it has a more prominent advantage than conventional drilling

(2) The gas extraction effect under different extraction time, different gas pressure, different negative extraction pressure, and different coal permeability was analyzed. It was found that with the increase of extraction time, the influence range of directional drilling gradually increased and the pressure gradually decreased. After 800 days, the middle area of the two boreholes was basically effectively drained. However, there are weak areas in the corner of the borehole and between the two boreholes with large spacing. It is necessary to increase the extraction time or improve the borehole design to eliminate these areas so as to achieve effective extraction of all coal. In addition, the simulation analysis of coal extraction process under three kinds of gas pressure (1.5 MPa, 2.5 MPa, and 3.5 MPa) shows that when the gas pressure is 1.5 MPa, after a period of extraction, the area with pressure less than 0.74 MPa around the borehole is the largest, followed by 2.5 MPa coal and 3.5 MPa coal. Therefore, the higher the coal gas pressure, the longer the time required to reach the standard of extraction

(3) The negative pressure of extraction was analyzed by numerical simulation. The negative pressure of extraction used in directional drilling of Baode Mine is about 33 KPa, and 13 KPa, 23 KPa, and 43 KPa were selected for comparative analysis. The results show that the increase of negative drainage pressure will make the decrease range of gas pressure around borehole become larger, but because of the low permeability of coal seam itself, the above effect is limited, so there is no need to pursue excessively large negative drainage pressure. Meanwhile, the gas extraction process of directional drilling was simulated with three different coal permeability (0.385 mD, 3.85 mD, and 38.5 mD). When the permeability was 0.385 mD, the influence range of gas extraction was the smallest. Until 800 days after extraction, the gas extraction still failed to reach the standard. However, when the permeability is 38.5 mD, the gas around the borehole decreases greatly, and the influence range of extraction increases rapidly. Therefore, for the coal body with high permeability, the extraction time can be appropriately shortened

Data Availability

Data are available from the corresponding authors.

Conflicts of Interest

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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