Hindawi
Advances in Civil Engineering
Volume 2018, Article ID 1912383, 7 pages
https://doi.org/10.1155/2018/1912383

Research Article

Study on Permeability Improvement Technology by Injecting Air into the Gas Drainage Borehole in Low-Permeability Coal Seam

Li Hui,[1,2,3] Guo Chengwei ,[1] Sun Yuanfang,[1] and Guo Shaoshuai [1]

[1]*School of Safety Science and Engineering, Henan Polytechnic University, Jiaozuo 454000, China*
[2]*State Key Laboratory Cultivation Base for Gas Geology and Gas Control, Henan Polytechnic University, Jiaozuo 454000, China*
[3]*Henan Province Collaborative Innovation Center of Coalbed Methane and Shale Gas for Central Plains Economic Region, Jiaozuo 454000, China*

Correspondence should be addressed to Guo Shaoshuai; 1498417843@qq.com

Received 24 March 2018; Accepted 27 May 2018; Published 12 September 2018

Academic Editor: Guang Xu

Gas extraction cycle is too long in low-permeability coal seam. In order to solve the problem, the basic principle about gas drainage drilling for gas injection technology is studied to increase permeability. And the mathematical model is established. Gas is injected into the low-permeability coal seam by numerical simulation. The results indicate that the best condition is a negative pressure drainage at 26 kPa and a gas injection pressure at 0.6 MPa in the vertical direction and in the horizontal direction of the injection hole. In Shanxi Daping Coal Mine 3113 working face, the field test is implemented. As a result, the test is successful. During the 14 d gas injection constantly, gas content of coal seam is reduced from 12.33 m^3/t to 7.12 m^3/t, greatly reducing the risk of coal and gas outburst elimination time required.

1. Introduction

At present, the overall situation of gas extraction in China is bad, mainly because of the low-permeability of coal seam [1]. China coal seam permeability is less than 1 mD accounted for 82%, 2-3 orders of magnitude lower than the United States [2, 3]. Low-permeability coal seam has the characteristics of low pressure, low permeability, and low saturation, and improving the permeability of coal seam is a big problem. This has a direct impact on the process of improving gas extraction rate and preventing and controlling gas disaster. Gas injection technology for permeability enhancement is a new type of permeability increasing technology, which could increase the permeability of coal seam effectively [4].

The technology of gas injection and permeability enhancement has been developed from the field of coal bed methane development. In 1970s, Americans injected CO_2 into the coal seam in the San Juan basin to improve CBM recovery and achieved good results [5]. America, Japan, Canada, and China have conducted different degrees of research, but the research on displacement mechanism of gas injection mostly adopts the method of theoretical analysis and numerical simulation [6–9]. No field tests are carried out, and the effect verification is lacking. Therefore, further improvements are still needed. Since 2007, Yang Hong-min of Henan Polytechnic University had applied gas injection to replace coal seam gas technology in the field of coal mine gas control. Field tests were successfully carried out [10–12], such as gas injection to eliminate outburst danger and gas injection to promote gas drainage, and certain effect was achieved. But, they were not ideal.

This paper aims at solving the low-permeability coal seam existing drainage problems in large quantities in China, through the study of gas injection to increase permeability mechanism and model of gas drainage drilling holes. The mathematical model of gas drainage drilling through gas injection is constructed for low-permeability coal seam, and the numerical simulation analysis is carried out. According to the actual situation of mine, this paper adopts the test method of injecting compressed air into the gas drainage borehole and carries out field test in the 3113 Lane driving face of Daping Mine in Shanxi Province.

2. Theory of Gas Injection Technology for Improving Permeability

The mechanism of gas injection technology to improve permeability is mainly based on the different adsorption capacities of CH_4, CO_2, N_2, and other gases. And the competitive adsorption, displacement desorption, and mutual displacement are analyzed. The adsorption capacity of coal to CH_4, CO_2, and N_2 was $CO_2 > CH_4 > N_2$ in turn. A large number of studies have shown that CO_2 and N_2 have great differences in the displacement and displacement of CH_4 in coal seams [13].

(1) The adsorption constant of CO_2 is larger than that of CH_4, and CO_2 has obvious advantage in gas competition absorption in coal seam. The mechanism of enhancing the permeability by CO_2 injection into coal seam mainly is that, on one hand, CO_2 can displace the free CH_4 in coal seam by pressure displacement; on the other hand, it can displace CH_4 adsorbed on coal body through CO_2. Thus, CO_2 is retained in the coal seam, and CH_4 is displaced out of the coal seam, thus increasing the permeability of the coal seam.

(2) N_2 has a disadvantage in competing with CH_4. First of all, the displacement of CH_4 by N_2 is driven and carried by pressure gradient. Secondly, after the N_2 was injected into the coal seam, the concentration difference was formed, and N_2 and CH_4 were diffused and "displaced" inwards and outwards under the action of concentration difference. Finally, after N_2 injection into the coal seam, partial pressure of CH_4 is reduced to produce the competitive adsorption of multiple gases. In these three aspects, N_2 completed the displacement of CH_4 to have increased permeability of coal seam.

Because the proportion of N_2 in air accounts for 79.8% and it is very convenient to obtain compressed air under the mine, the air injection is selected to enhance the permeability. Therefore, the numerical simulation process uses air as the simulation condition, and the compressed air in the compressed air system is taken as the gas source to conduct the field gas injection permeability enhancement test.

3. Mathematical Model of Gas Injection for Improving Permeability

According to the theory of seepage mechanics, seepage Darcy law, Fick's law of diffusion and multicomponent gas adsorption equilibrium theory, the law of conservation of mass and the ideal gas equation, the paper constructs the continuity equations of gas injection and permeability enhancement model and establishes the model of gas injection and permeability enhancement in low-permeability coal seam.

3.1. Seepage Equation of Gas in Fracture. It is assumed that the migration of free gas in the fracture can be regarded as a fluid percolation process, and the mass conservation equation of gas flowing through coal is

$$\frac{\partial m_i}{\partial t} + \nabla(\rho_i v) = Q_i \quad (i = 1,\ 2), \tag{1}$$

where ρ_i is the density of gas component i (kg/m^3), v is the total seepage velocity of gas (m/s), and m_i is the content of free gas component i (kg/m^3). $m_i = \varphi\rho_i$, where φ is the porosity.

3.2. Adsorption Equilibrium Equation of Multicomponent Gas. The content m_{pi} of adsorbed component under the assumed equilibrium pressure p_i can be expressed by the generalized Langmuir isotherm adsorption equation as

$$m_{pi} = \frac{\rho_i\rho_c a_i b_i p_i}{1 + b_1 p_1 + b_2 p_2}, \tag{2}$$

where ρ_i is the density of coal (kg/m^3), a_i is the individual ultimate adsorption capacity of component i in coal seams (m^3/kg), b_i is the adsorption constant of component i (MPa^{-1}), p_1 and p_2 represent the partial pressure of gas components 1 and 2, respectively.

3.3. Mass Exchange Equation. The mass exchange between adsorbed gas on the surface of coal and free gas in the fracture system can be defined as

$$Q_i = \left(c_i - m_{pi}\right)\tau, \tag{3}$$

where τ is the desorption diffusion coefficient, $\tau = 1.42$.

3.4. Equation of State for Ideal Gas. Because the gas injection pressure is small, the gas compression process can be ignored, and gas can be regarded as ideal gas. The equation of state of ideal gas can be expressed as

$$\rho_i = \frac{M_i p_a}{RT_a}, \tag{4}$$

where M_i is the molar mass of the gas component i (g/mol), R is the universal gas constant, p_a and T_a are the gas pressure and temperature under the standard conditions, respectively. $p_a = 0.1$ MPa and $T_a = 273$ K.

3.5. Seepage Velocity Equation. As the gas component flows in the coal body that conforms to Darcy's law, the total gas seepage velocity v is

$$v = -\frac{\nabla pk}{\mu_i}, \tag{5}$$

where k is the permeability of coal body (m^2), μ_i is the dynamic viscosity coefficient for gas component i (Pa·s), and p is the total pressure (gas injection pressure, MPa), $p = p_1 + p_2$.

3.6. Cross-Coupled Equation. Substituting (2)–(5) into (1), we can obtain simultaneous equations with cross coupling

$$\frac{\varphi M_i}{RT_{\mathrm{a}}}\frac{\partial p_i}{\partial t} - \nabla\left(\frac{M_i k p_i}{RT_{\mathrm{a}}\mu_i}\nabla p\right) = Q. \quad (6)$$

3.7. Diffusion Equation of Gas in Porous Media. Assuming that the motion of the adsorbed gas agrees with Fick's diffusion law, we can see that the diffusion equation of CH_4 and N_2 in the pore system is the equation of diffusion:

$$\frac{\partial c_i}{\partial t} + \nabla\left(-D_i \nabla c_i\right) = -Q_i \quad (i = 1,\ 2), \quad (7)$$

where i is the gas component, $i = 1$ represents CH_4, $i = 2$ represents N_2, c_i is the mass concentration (kg/m^3), D_i is the diffusion coefficient (m^2/s), t is the gas injection time, ∇ is the Hamiltonian operator, and Q_i is the Huiyuan item.

According to the reasoning analysis, (6) and (7) constitute the continuity control equation of gas permeability enhancement in low-permeability coal seam.

4. Numerical Simulation and Analysis

4.1. Geometric Model and Related Parameters. Because the gas permeability enhancement model is a three-dimensional structure, in order to facilitate the simulation, we simplify the model to a two-dimensional geometric model and select the radial study of drilling. The geometric model of gas injection and permeability enhancement is shown in Figure 1.

In order to facilitate the comparison between numerical simulation and field test and to better solve practical problems, the parameters in the simulation are all used in Shanxi Daping Coal Mine. The other parameters are obtained by referring to the data, and the specific parameters are shown in Table 1:

4.2. Initial Conditions and Boundary Conditions. The geometric model selected in the simulation experiment is 2 m high and 3.6 m wide. The borehole layout is revealed on the coal face in the heading face, as shown in Figure 1. We set two gas injection holes, and the surrounding boreholes are all empty. The distance between the injection hole and the horizontal drainage hole is 0.6 m. The initial adsorption gas content is 12.33 m^3/t. The drilling depth was 100 m.

4.2.1. Initial Condition. The original methane pressure of coal seam is p_0. The pressure injected into compressed air is 0 kPa.

4.2.2. Boundary Condition. The numerical model has a zero flow boundary. The atmospheric pressure in the mine is 0.1 MPa. The boundary conditions of the drainage holes, respectively, are 18 kPa, 22 kPa, 26 kPa, and 30 kPa. The boundary conditions of the gas injection holes, respectively, are 0.2 MPa, 0.4 MPa, 0.6 MPa, and 0.8 MPa.

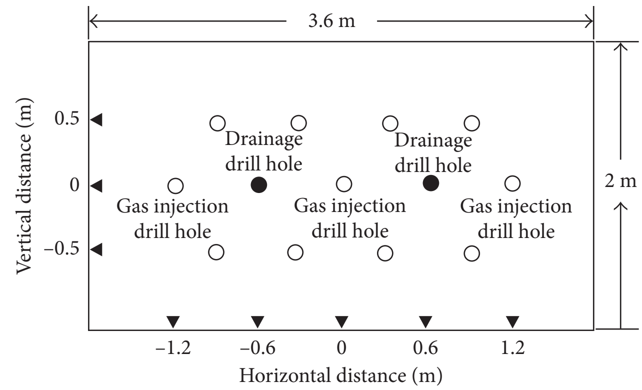

FIGURE 1: Plots of gas injection to improve the permeability model.

TABLE 1: Parameters for coal and gas in need.

Parameter	Value
Density of coal body, ρ_c	1.38×10^3 kg·m^{-3}
Porosity of coal body, φ	0.0320
Permeability of coal body, k	1.35×10^{-17} m^2
Density of CH_4 in the standard condition, ρ_1	0.717 kg·m^{-3}
Dynamic viscosity coefficient of CH_4, μ_1	1.03×10^{-5} Pa·s
Ultimate adsorption capacity of CH_4	
In coal seam adsorption alone, a_1	0.03832 m^3·kg^{-1}
Adsorption equilibrium constant of CH_4, b_1	0.51 MPa^{-1}
Density of N_2 in standard condition, ρ_2	1.25 kg·m^{-3}
Dynamic viscosity coefficient of N_2, μ_2	1.69×10^{-5} Pa·s
Ultimate adsorption capacity of N_2	
In coal seam adsorption alone, a_2	0.01658 m^3·kg^{-1}
Adsorption equilibrium constant of N_2, b_2	0.46 MPa^{-1}
Pressure of gas in standard condition, p_a	0.101325 MPa

4.3. Results of Numerical Simulation. Using the established mathematical model, the numerical simulation software is used for the simulation analysis. In the horizontal direction and vertical direction of gas injection, we simulate the variation of gas content in coal seam under different pumping negative pressure and different gas injection pressure and get the time needed to eliminate outburst danger. In order to facilitate detection, in the horizontal direction, we choose distance gas injection hole 0.8 m as the gas content detection position and choose distance gas injection hole 0.4 m as gas content detection position in the vertical direction.

4.3.1. In the Horizontal Direction. In the negative pressure of 26 kPa and gas injection pressure of 0.8 MPa, we simulate the gas injection pressure of 0.2 MPa, 0.4 MPa, and 0.6 MPa. And in the gas injection pressure of 0.6 MPa, the negative pressure of 18 kPa, 22 kPa, and 26 kPa are respectively simulated. The changes is 30 kPa vacuum extraction in the horizontal 0.8 m of gas injection hole. The simulation results are shown in Figure 2.

4.3.2. In the Vertical Direction. We set up the same test conditions as the suction pressure and gas injection pressure in the horizontal direction and had analyzed the change of

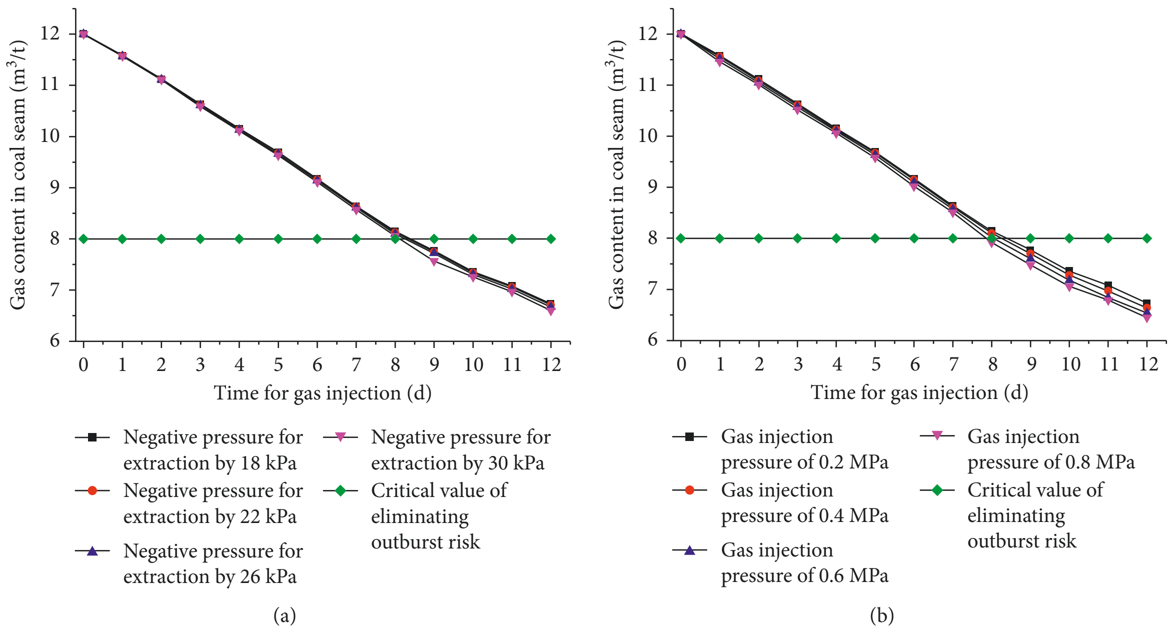

Figure 2: Plots of content variation of gas at 0.8 m in the horizontal direction of gas injection. (a) Influence of different negative pressure on eliminating outburst risk. (b) Influence of different gas injection pressure on eliminating outburst risk.

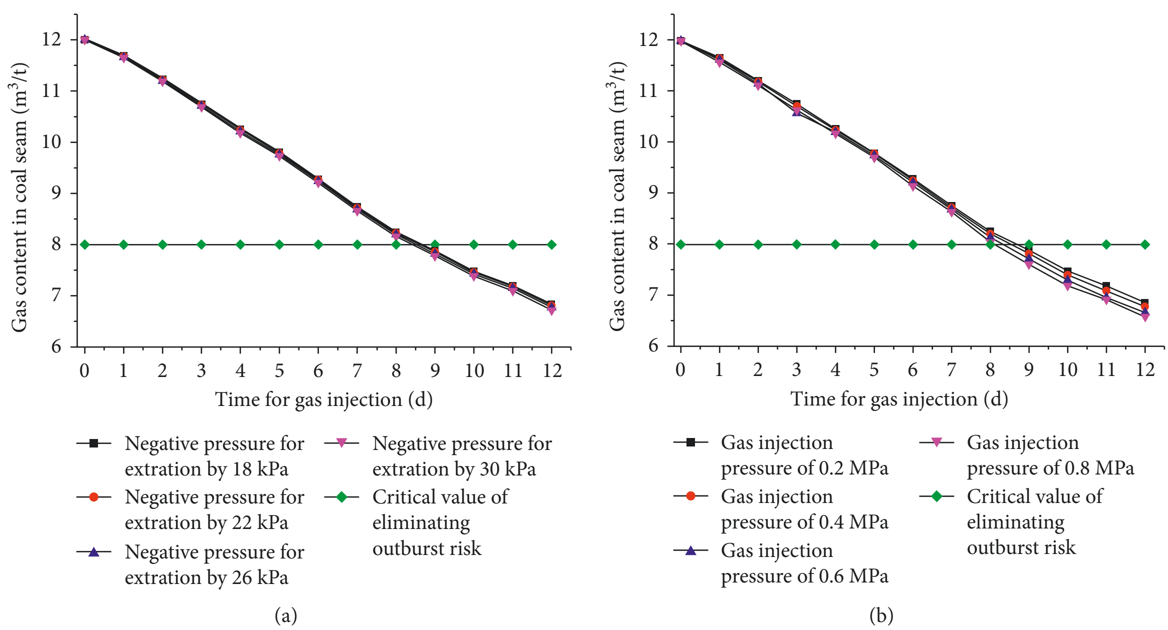

Figure 3: Plots of content variation of gas at 0.4 m in vertical direction of gas injection. (a) Influence of different negative pressure on eliminating outburst risk. (b) Influence of different gas injection pressure on eliminating outburst risk.

gas at 0.4 m in the vertical direction of the gas injection hole. The simulation results are shown in Figure 3.

From Figure 2 we can obtain that, in the horizontal direction, firstly, negative pressure is negatively correlated with coal seam gas content. When the suction pressure increases from 18 kPa to 30 kPa, the gas content at 0.8 m in the horizontal direction decreases by 0.13 m^3/t. The outburst cycle is shortened for 6.5 h after 12 days of gas injection. Secondly, the gas injection pressure is negatively correlated with the gas content of the coal seam. When the injection pressure increases from 0.2 MPa to 0.8 MPa, the gas content in the horizontal direction 0.8 m decreases by 0.28 m^3/t. The outburst prevention cycle 12.7 h is shortened. When the injection pressure is about 0.6 MPa and the suction pressure is about 26 kPa, the effect of eliminating outburst danger is most obvious. Therefore, it can be concluded that this scheme is the best scheme for gas permeability enhancement in low-permeability coal seam.

From Figure 3, we can obtain that the vertical direction is similar to the horizontal direction and the gas content of coal seam is negatively correlated with the negative pressure of drainage. When the suction pressure increases from 18 kPa to 30 kPa, the gas content in the vertical direction 0.4 m decreases by 0.12 m^3/t and the outburst prevention cycle 5.9 h is shortened after 12 days gas injection. Gas content is also negatively correlated with gas injection pressure. However, the influence coefficient of gas injection pressure is smaller in the horizontal direction due to gravity. When the injection pressure increases from 0.2 MPa to 0.8 MPa, the gas content in the vertical direction 0.4 m decreases by 0.19 m^3/t and the outburst prevention cycle 14 h is shortened. When the injection pressure is about 0.6 MPa, the suction pressure is about 26 kPa and the effect of eliminating outburst danger is most obvious. Therefore, it can be concluded that this scheme is the best scheme for gas permeability enhancement in low-permeability coal seam.

From simulation we can find that, in both horizontal and vertical directions, negative pressure and gas injection pressure play an important role in reducing the gas content and reducing the time needed for outburst elimination. The influence coefficient of suction pressure is 0.076, and the influence coefficient of injection pressure is 0.178. Under the condition of ensuring safety and high efficiency, it is concluded that the suction pressure of 26 kPa and the injection pressure of 0.6 MPa are the best scheme.

5. Field Test

5.1. General Situation of Test Site. At present, the length of No.3113 roadway openings of Daping Coal Mine in Shanxi province is 1436 m. The elevation located in the southeast of the South slope is +390 m ~ +483 m. The coal seam belongs to low-permeability coal seam, whose average thickness of coal seam is 6.25 m. The actual measured gas content of coal seam is 12.33 m^3/t. The current mine drainage parameters are as follows: extraction negative pressure 18 kPa, gas extraction concentration 5.5%–6.5%, standard condition mixed flow 120 m^3/min–130 m^3/min, gas extraction pure 7-8 m^3/min, and 3113 Lane gas extraction 0.1 m^3/min.

5.2. Test Scheme. According to the actual production situation of Daping Coal Mine in Shanxi, the driving face of 3113 Lane is selected in the test site. According to research and design, the construction of drilling is three rows, 21 holes totally, which is divided by pumping holes and gas injection holes. All the drainage holes are used to test the gas concentration detection hole. The drilling depth is 100 m. We use 26 kPa suction negative pressure and 0.6 MPa injection pressure to enhance permeability test. During the test, the roadway should be reinforced to ensure the normal excavation, the gas prediction work should be done well, and emergency warning and related safety measures should be done. The specific drilling arrangement is shown in Figure 4.

5.3. Test Result. The effect of the permeability enhancement test of the gas drainage borehole in low-permeability coal seam is mainly achieved by measuring the gas extraction volume fraction of the drainage hole and taking the average value. Because of the limitation of the length, we choose to analyze the drainage effect of 2#, 4#, and 6# drainage holes and 9#, 11#, and 13# drainage holes in the vertical direction. The measurement results are shown in Figures 5 and 6.

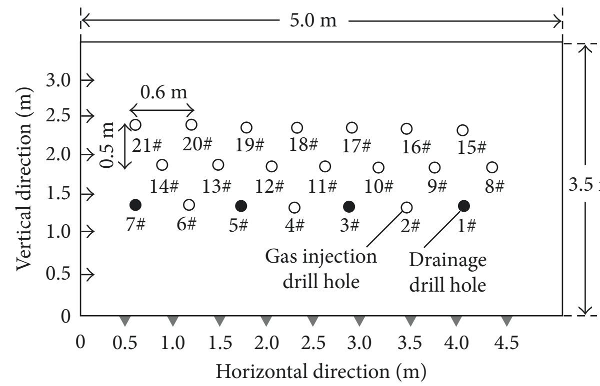

Figure 4: Plots of gas drainage borehole distribution.

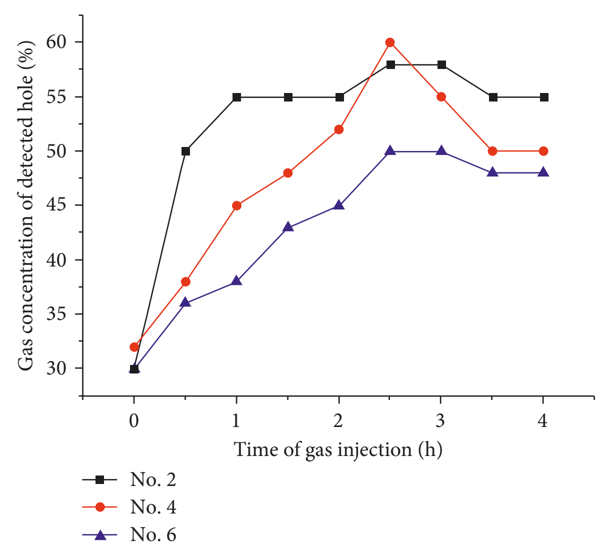

Figure 5: Plots of gas concentration variation in the gas hole during gas injection.

From Figure 5, we analyze the extraction effect of 2#, 4#, and 6# drainage holes: when the hole diameter is 113 mm, extraction pressure is 26 kPa, gas injection pressure is 0.6 MPa, injected gas is compressed air (mainly nitrogen), and mining hole gas volume fraction in the horizontal direction firstly rises smoke adjacent, reaches a maximum value, decreases slightly, and finally tends to a steady value. In general, there is a significant increase in the total growth rate of 4 h within 73.6%, which is consistent with the theoretical analysis and numerical simulation results. From Figure 6, we analyze the extraction effect of 9#, 11#, and 13# drainage holes: in the vertical direction, the gas volume fraction in the drainage hole firstly increases continuously, reaches a larger value, decreases slightly, then rises steadily, and finally tends to a steady value. On the whole, there is a significant increase, and the average growth rate in 4 h is 69.7%.

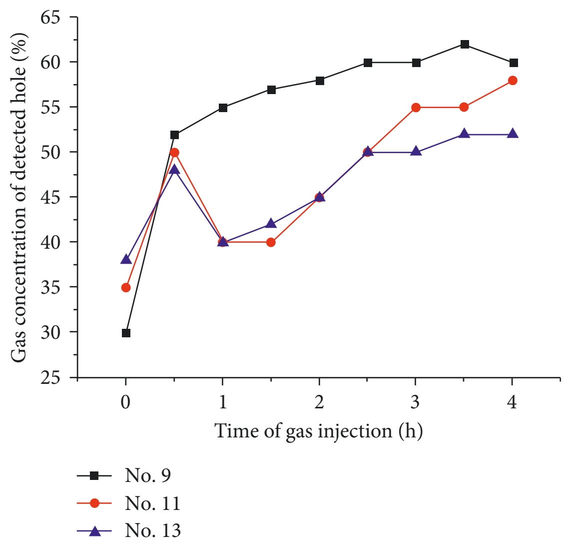

Figure 6: Plots of gas concentration variation in the gas hole during gas injection.

Then, in order to further verify the model of the drainage borehole gas injection scheme of the antireflective effect test in 3113 roadway heading face of Daping Mine in Shanxi Province, when the conditions are the gas injection pressure 0.6 MPa and the vacuum extraction 26 kPa, we continue to gas drainage drilling for gas injection side drainage boundary test for 14 days. As a result, the gas injection permeability enhancement test has achieved remarkable results. The coal seam gas content of the 3113 Lane driving face decreased from 12.33 m^3/t to 7.12 m^3/t, which greatly shortened the time needed to eliminate the risk of coal seam gas outburst. Although the required theoretical time is longer than the simulation, the specific conditions of the test are not completely consistent. In the error range allowed by the test, the field test of No. 3113 roadway heading face of Daping mine in Shanxi province has succeeded.

6. Conclusions

(1) According to the basic principle of borehole gas injection pump-type coal gas permeability of low permeability, and on the basis of gas seepage mechanics, gas adsorption theory, gas diffusion theory, and law of energy conservation and mass conservation theory, we establish the mathematical model through the coal seam gas injection in low permeability increase.

(2) The simulation software is used to simulate the influence law of gas on the gas content in coal seam under the condition of gas injection in the side of the gas drainage borehole. The influence law of different pumping negative pressure and gas injection pressure on eliminating outburst danger is simulated. It is concluded that the negative pressure and gas injection pressure have a significant effect on shortening the outburst cycle, and the negative pressure of 26 kPa extraction and the injection pressure of 0.6 MPa are the reasonable parameters for gas permeability enhancement in low-permeability coal seams.

(3) Through the field test in 3113 roadway heading face of Daping mine in Shanxi Province, it is concluded that gas injection and permeability increase in the gas extraction borehole of low-permeability coal seam can obviously improve the gas volume fraction in the drainage borehole in a short time. And after continuous gas injection test, the gas content of the coal seam decreased from 12.33 m^3/t to 7.12 m^3/t, which greatly shortened the time needed for outburst elimination.

Data Availability

The data used to support the findings of this study have been deposited in the Scientific Data's List of Recommended Repositories repository (DOI https://figshare.com/account/home#/collections).

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

This work was supported by the National Natural Science Foundation of China (no. 51474098).

References

[1] T. Xianglong, S. Dongri, and C. Dingliang, "Extracting coalbed methane from low permeability seam by water injection," *China Coal*, vol. 6, pp. 12-13, 2009.

[2] W. Sipeng, "Study on fracturing technology to improve permeability in coal seams with low permeability," *China Coal*, vol. 7, p. 101, 2010.

[3] F. Zengchao, *Theory and Application of Gas Enhanced Extraction in Low Permeability Coal Seam*, Science Press, Beijing, China, 2008.

[4] W. Shiyue and G. Yongyi, "Study of the mechanism of increasing production of exploitation coal-bed methane by gas injection," *Journal of China Coal Society*, vol. 6, pp. 12-13, 2009.

[5] C. R. Clarkson and R. M. Bustin, "Binary gas adsorption/desorption isotherms: effect of moisture and coal composition upon component selectivity over methane," *International Journal of Coal Geology*, vol. 42, no. 4, pp. 241–272, 2000.

[6] C. Xiaojun, B. R. Marc, and D. Gregory, "Selective transport of CO_2, CH_4, and N_2 in coals:insights from modeling of experimental gas adsorption data," *Fuel*, vol. 83, no. 3, pp. 293–303, 2004.

[7] Z. Ailing, W. Xinhai, and L. Dehua, "Research on numerical simulation of enhanced coalbed methane recovery by injecting gas," *Petroleum Drilling Techniques*, vol. 31, no. 2, pp. 55–57, 2006.

[8] D. Junzhen and L. Jianjuni, "Numerical simulation based on COMSOL Multiphysic to steady and non-equilibrium adsorption-mobilization of coalbed methane," *China Coalbed Methane*, vol. 4, no. 3, pp. 25-26, 2007.

[9] S. Keming, P. Yishani, and L. Bing, "Numerical simulation of deep coal-bed methane multi-well exploitation under fluid-solid coupling," *Chinese Journal of Rock Mechanics and Engineering*, vol. 26, no. 5, pp. 994–1001, 2007.

[10] Y. Hong-min, Z. Tie-gang, and W. Zhao-feng, "Experimental study on technology of accelerating methane release by nitrogen injection in coalbed," *Journal of China Coal Society*, vol. 35, no. 5, pp. 792–796, 2010.

[11] X. Hui-hui, Y. Hong-min, and Z. Wen-qing, "Strengthen pre-drainage coal roadway bands CH_4 technology by gas injection coordinated with boreholes along seam," *Safety in Coal Mines*, vol. 43, no. 6, pp. 35–37, 2012.

[12] Y. Hong-min, X. Hui-hui, and W. Zhao-feng, "Influencing factors on time-varying characteristics of displacement coalbed methane by gas injection," *Journal of Mining and Safety Engineering*, vol. 30, no. 2, pp. 273–277, 2013.

[13] Y. Hong-min, W. Chen-hui, and W. Zhao-feng, "Numerical simulation of coal-bed methane displacement by underground gas injection based on multi-physics coupling," *Journal of China Coal Society*, vol. 35, pp. 109–114, 2010.