MSc Thesis

Numerical Simulation of Coal-Seam Gas Drainage Based on Solid-Gas Coupling Model

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Declaration of Authorship

„I declare in lieu of oath that this thesis is entirely my own work except where otherwise indicated. The presence of quoted or paraphrased material has been clearly signaled and all sources have been referred. The thesis has not been submitted for a degree at any other institution and has not been published yet."

Abstract

Gas drainage is one of the important methods to prevent gas accidents in coal mines. In order to accurately reflect the gas migration law of the gas drainage process in the bedding and determine the reasonable boreholes layout parameters, the gas-solid coupling model of coal gas seepage was established with gas dynamics introduced diffusion coefficient, based on the coupling effect of elastic media with dual-pores and dual-permeability and combined with coal body deformation and permeability evolution. COMSOL Multiphysics was used to simulate gas drainage process in the bedding to explore the influence of different factors on the gas migration. According to the simulation results, the changing trends of coal seam gas pressure and permeability during the gas drainage process were analyzed under the different conditions including drainage time, negative pressure and boreholes diameter.

Keywords: Gas drainage, Solid-gas coupling model, Numerical simulation, Gas pressure, Permeability

Table of Contents

1. Introduction

1.1 Background and Significance

China is the largest producer of coal in the world today, accounting for more than 35% of the world’s coal output, and coal has always accounted for more than half of the primary energy production and consumption (Chen Qian, 2017). At the same time, China is also the country with the largest consumption of coal in the world. In recent years, due to various impacts such as the regulatory policies of relevant departments of China on the total amount of coal, the total consumption and output of coal in China's coal industry have declined, but coal is still the main energy in China (Guo Jianli, 2017). Nowadays, China's coal mining is gradually changing from shallow mining to deep mining. With the increasing of mining depth, the geological conditions of coal seam are more complex and changeable, and the gas content also increases. Therefore, gas has become the most important factor threatening the safety of coal mine production and workers' lives.

As an important task in coal mine production, gas drainage in coal seam has become the main measure to prevent and control gas accidents, and borehole gas drainage has also become the effectively methods to extract gas from coal seam and adjacent layers at home and abroad, among which borehole drainage is the most widely used and more common method. Although China has made great progress and development in gas drainage technology, there is still a shortage of gas drainage theories and a great limitation in research methods (Liang Bing, 2015). China's overall level of gas drainage and the drainage effect still is not very ideal, embodied poor occurrence condition in coal seam, low permeability, backward gas drainage technology, lower gas utilization rate and insufficient funds. Therefore, it is very important to choose a reasonable and efficient methods of gas drainage (Zhang Meihong,2015; Hou Zhenhai,2016; Hu Yanwei,2018; Cai Peipei,2017). By building a mathematical model of gas migration in the process of gas drainage and using simulation software to predict and analyze the drainage effect under various parameters, the simulation results can be effectively applied to the pre-drainage of coal seam gas, so as to reduce the content of gas in coal seam and the occurrence of gas accidents.

Deep coal mining in our country has a "high stress, high gas content, strong adsorption, low permeability," etc., greatly increased the difficulty of gas control and mining difficulty (Hu Shaobin,2015; He Manchao,2010; Yanghui Ren,2017). Gas disaster management and gas borehole drainage are based on gas migration law. The porosity and permeability are often the key indicator to measure the difficulty of gas drainage and also the important parameters of gas migration under the field coupling. The gas drainage in the process of the change of porosity and permeability is very complex, which is caused by the coupling of gas migration and solid deformation (Meng Ran,2015; Gang Wang,2018; Yin Zhiguang, 2013; Hai-tao WANG,2017). At the same time, coal seam gas pressure, drainage methods and the difference of borehole arrangement also directly affect the drainage process of gas seepage, thus influencing the effect of the gas drainage. So by coupling gas migration and gas seepage law can not only develop and enrich the related theory, at the same time can be applied to engineering practice to fundamentally eliminate gas accident hazard in coal mine.

1.2 Research status

1.2.1 Research Status of Gas Migration Law

The study of gas migration theory is of great significance to gas disaster prevention and safety production. Coal seam is a low-permeability material with complex pore and fracture structure, with both nanoscale pores and millimeter fractures in the interior, so the migration mechanism of gas in it is very complicated (Wei Jianping,2016; Ni Xiaoming,2017). The main purpose of the study of gas migration theory is to explain the natural law of gas migration and the phenomenon of gas emission in coal seam, so as to provide a theoretical basis for the prevention and control of gas disaster. At present, domestic and foreign researches on the theories of coal seam gas migration mainly include linear, nonlinear and multi-field coupled gas migration theories (Meng Lei,2013).

In the middle of the 20th century, scholars from the former Soviet Union first proposed to use Darcy law to describe the seepage movement of gas in coal seam. The law of gas migration and accumulation in coal seam is the theoretical basis for gas control in coal mine, although have been research for years, still not a perfect and independent system. After scholars studied the gas migration theory of a large number, they have put forward a series of the gas migration law in coal seam, such as Darcy law, Fick law, power law and permeation-diffusion law. Zhou Shining regarded regards the coal seam with porous media as a kind of virtual continuous medium with uniform distribution on a large scale and proposed the current gas migration theory of coal seam on the basis of Darcy law (1965). In order to better conform to the actual situation of gas migration in coal seam, scholars have continuously improved and revised the linear gas-flow equation (Yuewu Liu, 2009; Zhou Shining,1965). Guo Yongyi combined with the size-like theory, the complete solutions of four kinds of gas seepage field equations are obtained in one dimension(1984), at the same time, Langmuir gas adsorption equation was used to calculate the amount of gas adsorption at isothermal temperature, and the gas flow equation was modified (Yuewu Liu, 2009). In order to study the gas diffusion and flow characteristics in longwall working face, Wang et al. used CFD to conduct modeling research on six typical longwall mining types (2017). Luo Xinrong took into account the phenomenon of gas slipage and used it as the theoretical basis to modify the governing equation of gas flow in coal seam (1991). Sun Peide proposed a nonlinear gas seepage theory that is more consistent with the actual situation gas flow in coal seam than Darcy law (1987). He Xueqiu et al. classified the types of gas diffusion in coal according to the gas diffusion mechanism (2001). At present, domestic and foreign hot spots focus on the development and creation of the gas seepage theory of coal seam under the action of multi-physical field and multi-phase coupling. Among them, Meng et al., in order to reveal the seepage law of raw coal under different gas pressure, developed and applied the experimental seepage system of gravitational constant load, and found that with the increase of gas pressure, the permeability of coal sample decreased significantly and showed an upward trend when it reached the extreme value (2015). Wang et al. considered the effective stress and pore pressure on the resistance of gas migration and derived the theoretical expression of gas migration resistance (2017). Li Sheng et al. regarded coal and rock as a dual structure with pore-fracture and inhomogeneous elastic medium with double permeability, established a dual-pore and dual-permeability model with consideration of matrix gas seepage and carried out simulation, believing that the model was more in line with the actual situation of gas migration in coal seam (2018). Based on the study of gas-solid coupling, Tao Yunqi proposed the three fields coupling of heat gas-solid under the action of temperature, ground stress and gas pressure, building the model, and pointed out that the temperature cannot be ignored during deep mining (2019).

In order to study the law of coal seam gas flow, Wei Jianping et al. built a gas flow model with percolation-diffusion effect on the premise of different diffusion mechanisms and slip boundaries (2016). The ways of gas migration in coal seam include diffusion and seepage. According to the theory of gas seepage and diffusion, the gas flow in coal seam is a mixture of seepage and diffusion. According to the relationship between ground stress and porosity, numerical simulation is carried out to make the modified simulation results more consistent with the actual situation. Zhang Li built seepage and diffusion equation from the point of view that the gas follows Fick diffusion law and the fracture follows Darcy law (2017). Lin Boquan et al. synthesized the previous research and combined with the actual production, expounded the theory of gas seepage and diffusion model (2018). The flow of gas in coal is formed by gas migration under the action of solid-gas coupling. As a kind of multi-void medium, the physical and mechanical properties of coal are very complicated. Scholars have done a lot of research on gas migration under the action of solid-gas coupling, so as to analyze the relationship between coal deformation and gas migration and the basic law of coupling movement (Tao Yunqi,2009; Qei Jianping, 2016; Qiu Yang, 2016). In order to understand the gas-solid coupling law of deep coal seam, Zhou and Wang et al. built gas-solid coupling model under the influence of ground stress, gas pressure and mining depth by using COMSOL Multiphysics software, and carried out simulation, providing theoretical basis for the gas prevention. Guo ping et al. studied the influence of adsorption swelling effect and Klinkenberg effect on gas migration and established the solid-gas coupling model of coal with gas, and the results show that the matrix gas pressure decreases with the increase of the natural unloading time, and the porosity and permeability of coal increase with the increase of the natural unloading time. Yang Xiaobin et al. carried out numerical simulation of gas-solid coupling and believed that when gas-bearing coal mass is in the elastic stage, the permeability of coal rock increases with the increase of strain volume. Zhang Bo et al. modeling the gas seepage, heat and fluidity in front of the working face, and analyzed the change law of gas pressure and permeability in coal seam and believed that the porosity and permeability of coal in the stress concentration area were relatively low. Hu Shaobin built the mathematical physical model of gas-solid coupling with multi-scale fractured coal, and revealed the coupling dynamic disaster process and mechanism of coal and gas. Xu Tao and Yang Tianhong et al. considered the evolution process of coal body fractures, modeling the coal-bed gas solid coupling with damage, and carried out the gas drainage process of deep coal seam. Based on the theory of synchronous migration of coal seam gas diffusion and seepage, Zhang Meihong et al. built a gas-solid coupling mathematical model for gas drainage and carried out simulation with a coal mine in Jincheng, Shanxi Province as an example, providing a theoretical basis for optimizing gas drainage. To sum up, only by establishing the gas-solid coupling model of coal and gas, the relationship between the analysis of coal body deformation and gas migration, to further understanding the gas migration law, permeability, porosity and other characteristics in the process of gas drainage, to provide important theoretical basis and practical value for gas drainage and gas dynamic disaster prevention.

1.2.2 Research Status of Gas Slippage Effect

The gas slippage effect is the phenomenon when the gas flows in small capillary or low permeability porous medium. Maxwellzai in 1867 first discovered the phenomenon of gas slip near the solid wall. In 1941, Klinkenberg applied Knudsen diffusion to the study of problems in the field of petroleum engineering and defined the slippage effect as the phenomenon that the velocity of gas molecules is not equal to zero near the surface of pore wall, and believed that this phenomenon led to the gas permeability in the rock being greater than the liquid permeability, and obtained the classical Klinkenberg equation. Alireza Ashrafi Moghadam et al. derived the new equation by summarizing others' theories, and successfully predicted the deviation of Klinkenberg equation in low permeability medium, and verified it by experiments. Taking the low-permeability sandstone gas as the research object, Lv Zhikai et al. designed a new method for the establishment of water saturation in the core, and studied the variation law of water saturation, effective stress and coupling effect of the two on the gas slippage effect in the low-permeability rock. Xiao Xiaochun, adopt the method of experimental study to test slipage of low permeability of coal sample, to study the effect of confining pressure and pore of coalbed gas slippage effect, and analyzed the influence of slippage permeability on gas permeability, under different confining pressure and pore water pressure, found the favorable confining pressure range of slippage effect on gas permeability in different low-permeability reservoirs, and verified the universality of gas slippage effect in each case with low permeability. Moghadam and Ziarani et al., based on the application conditions and application objects of Klinkenberg equation, respectively put forward corrections. Yuan Zhe et al. explained the effect of effective stress and gas slippage on the control of permeability variation through experiments on gas-phase permeability variation of different coal samples. By analyzing the research of gas slippage effect, Ran Yanxia et al. summarized the mechanism and conditions of the slippage effect, and believed that the movement state of gas molecules near the pore wall was the fundamental cause of the slippage effect. At the same time, the influence and essence of gas slippage effect were comprehensively analyzed by focusing on factors such as pore gas pressure, confining pressure, water saturation and gas properties.

1.2.3 Research Status of Gas Drainage Numerical Simulation

Rock gas outburst becomes more and more serious with the increase of mining depth, so the gas disaster is an important hidden trouble that affects the safe production of coal mine. Gas drainage is the main measure to prevent and control gas disasters, and extracting gas from coal seams in an efficient way is the key to reduce the occurrence of gas disasters. Pre-drainage and co-mining of coal and gas have become the key link to ensure the coal mine benefit. At the same time, the gas drainage will reduce the ventilation pressure to a certain extent and save some ventilation costs. It has been proved by practice that borehole pre-drainage of gas is an extremely effective measure to prevent and control the occurrence of gas disasters, so the research on borehole parameters is of certain value for the use of borehole gas drainage in the prevention and control of coal mine gas disasters. Cheng Yuanping et al. considered the change of the negative pressure, combined with the parallel relationship between gas drainage and air leakage, and used Comsol Multiphysics to solve the model numerically, studied the change mechanism of the negative pressure in the gas drainage process, and obtained the change of gas concentration under different negative pressure. Dang Quanlin et al. established the gas flow equation of the coal body around the borehole and made use of COMSOL Multiphysics software to simulate, and obtained the effective drainage radius and the corresponding pre-drainage period for the borehole. Pang Yeqing et al. revealed the group hole effect of regional gas drainage boreholes through researching on the variation of gas pressure and porosity with gas drainage time in specific areas. In order to accurately and reasonably determine the layout parameters of borehole along the bedding, Meng Ran et al. established the mathematical model of seepage field of gas drainage along the bedding, carried out numerical simulation of gas drainage process along the working face, and determined a more reasonable layout method of gas drainage borehole in the coal seam. Hu Yanwei et al. used COMSOL Multiphysics software to simulate the distribution law of gas in goaf after dynamic equilibrium, and obtained the characteristics of gas distribution law in goaf, providing a basis for determining the gas control. Gao Yabin et al., in order to improve the drainage effect of crossing borehole in high-outburst coal seam, combined with the technical advantages of hydraulic punching and hydraulic cutting, put forward the "drilling-punch-cutting" coupling pressure relief technology for crossing borehole, and studied its coupling pressure relief effect by numerical simulation method. Considering the processes of gas desorption, migration, release and flow in the coal matrix and in the fractures, Qin Yueping et al. established the dual-permeability model of gas in the borehole of the coal body with dual-porosity, and developed the numerical simulation program by using the finite difference method, and revealed the gas flow mechanism in the coal body with dual-porosity. Liang Bing et al. built a seepage coupling model for gas drainage by comprehensively considering the skeleton deformation of coal and rock mass, gas compressibility and adsorption-desorption characteristics of coal gas, studied the law of gas migration in coal seam during drainage and provided theoretical basis for the rational arrangement of boreholes.

1.3 Main Research Content of This Thesis

This paper mainly adopts the method of combining theoretical modeling, experimental data verification and numerical simulation to carry out the gas seepage law of dual-porosity and dual-permeability coal seam based on the solid-gas coupling model and carry out the numerical simulation of gas drainage from boreholes. The specific research contents are as follows:

(1) To build a model of gas permeability with dual-porosity and dual-permeability based on the solid-gas coupling: based on the non-uniform elastic

medium that coal and rock are regarded as a dual-structure with pore-fracture and dual-permeability, modeling the gas-solid coupling model combined with the seepage field and stress field of gas migration. The theoretical model is verified with the experimental data and the law of gas seepage in coal is analyzed.

(2) To build the equation of gas permeability control of coupling model based on dual-porosity and dual-permeability, using COMSOL Multipysics software to study the result of the simulation, and analyze the influence of parameters, including gas drainage time, drainage pressure, the initial gas pressure and the borehole diameter, on pressure , porosity and permeability of drilling borehole in the process of gas drainage .

(3) Based on the study of gas permeability model and numerical simulation of solid-gas coupling with dual-porosity and dual-permeability coal seam, the COMSOL Multipysics platform is used to perform numerical simulation of gas drainage in multiple boreholes along the bedding. The gas permeability law and the influence of gas drainage in the process of gas drainage were studied by setting different spacing of boreholes, so as to find an efficient gas drainage method and provide a theoretical basis for gas drainage design.

(4) Based on the simulation results of gas drainage in the coal seam above, the application research of gas pre-drainage in the 2# coal seam of Fenxi Zhongxing coal mine was carried out, and the overall effect of gas drainage in the coal seam was analyzed.

2 Gas Seepage Coupling Model Based on Dual-porosity and Dual-permeability Theory

2.1 Physical Model

Gas drainage is an effective means to prevent gas accidents and ensure the safety of coal mines. The study of gas migration in the process of gas drainage can provide an important theoretical basis for gas drainage in coal mine, so as to improve the gas drainage efficiency and the efficient development of clean energy.

Gas migration in coal seam is affected by the pore structure of coal seam, which is complex and changeable. Therefore, the relationship between gas diffusion and seepage in different types of coal seam should be considered when studying the law of gas migration in coal seam. In addition, coal permeability is an important parameter in the study of the degree of difficulty and efficiency of gas drainage. In the preceding paper, the construction of coal permeability model has been described in detail. The existing gas seepage model fully considers the influence of porosity, coal structure, effective stress and other relevant factors on the evolution law of coal gas seepage.

Coal seam gas migration state and the pore structure of coal seam with high correlation, and the coal body structure is complicated in nature. Therefore, when studying the law of gas migration, scholars take the primary and secondary action of gas diffusion or seepage in different types of coal seams as the basis, and simplify the structure of pore and fracture into uniform pore medium model with only diffusion equation and uniform fracture medium model with only permeability. In recent years, the dual-medium model of pore and fracture has been gradually recognized by many scholars. The dual-medium model of pore and fracture are considered the gas migration in coal seam as a continuous process of diffusion and seepage. Firstly, the gas is diffused from coal matrix to the fracture in the form with Fick diffusion, and then it is transported to the borehole through the fracture in the form with Darcy seepage.

Considering the coal structure, gas migration mode and coal permeability comprehensively, the coal structure and gas migration mode can be classified as follows:

(1) Single-pore and single-permeability model: the coal structure is regarded as the homogeneous fracture medium model, and only the fracture permeability is considered. When the gas pressure in the coal seam changes, the coal matrix gas starts to desorption, diffusion and finally enters the coal body fracture, and the gas migration mode is only Darcy seepage.

(2) Dual-hole and single-permeability model: the coal body is regarded as a dual structure with both pores and fractures and a dual-permeability medium model. Considering only the fracture permeability, the gas migration process is regarded as a continuous process of diffusion and seepage.

(3) Dual-pore and dual-permeability model: the coal body is regarded as a dual structure with both pores and fractures and a dual permeability medium model. At the same time, both pore permeability and fracture permeability are taken into account.

At present, a large number of scholars generally believe that the coal seam matrix is double porosity, so the coal gas seepage model should meet the requirements of the dual-porosity and dual-permeability model. The "dual-pore and dual-permeability" system is a dual medium model that idealizes the coal structure into pore-fracture, and considers the gas transport mode in the coal fracture and the matrix pores, that is, the gas in the coal matrix not only enters the fracture in the form of diffusion, but also moves between the matrix through seepage and finally flows into the borehole.

Therefore, this article will be as a dual structure of pore-fracture of coal or rock and dual-permeability medium, combined with coupling the stress field and seepage field, thus gas seepage coupling model is set up, so as to research in the process of coal seam gas drainage in migration regularity and its influence on the gas drainage.

2.2 Fundamental Assumptions

1. The coal body is regarded as an inhomogeneous elastic medium with dual-pore and dual-permeability;

2. The gas in the coal matrix is an ideal gas, which occurs in adsorption state and free state， and migrates in the matrix pores and fractures.

3. The influence of gas volume force and temperature on gas drainage is not considered.

4. Gas flows into the fractures from the matrix through two ways -- seepage and diffusion. The diffusion follows Fick law and seepage follows Darcy law.

5. Gas adsorption/desorption is completed instantly, meeting the Langmuir adsorption equilibrium curve.

6. The strain is much smaller than the length of the model.

2.3 Modeling

2.3.1 Permeability Model

The porosity of the initial matrix is φ_{b0}, the gas pressure of the matrix is P_b, the initial matrix pressure is P_{b0}, and the initial volume strain is ε_{V0}, so the porosity of the coal matrix can be defined as:

$$\varphi_b = \frac{1}{(1+Q)}\left(\varphi_{b0}(1+Q_0) + \alpha_b(Q-Q_0)\right) \tag{2.1}$$

$$Q = \varepsilon_V + \frac{P_b}{K_s} - \varepsilon_L \frac{P_b}{P_L+P_b} \tag{2.2}$$

$$Q_0 = \varepsilon_{V0} + \frac{P_{b0}}{K_s} - \varepsilon_L \frac{P_{b0}}{P_L+P_{b0}} \tag{2.3}$$

φ_b—— The porosity of coal matrix;

φ_{b0}—— The initial porosity of the coal matrix;

α_b——The pore Biot coefficient;

Q——The pore stress variable of coal matrix.

Q_0—— The initial pore strain variable of coal matrix.

ε_V——The volumetric strain;

ε_{V0}——The initial volume strain;

K_s ——The bulk modulus of coal skeleton, Pa;

ε_L ——The strain constant;

P_L ——Langmuir pressure, Pa;

P_b ——The gas pressure of coal matrix, Pa ;

P_{b0} ——The initial gas pressure of coal matrix, Pa.

Permeability and porosity satisfy the following relationship, defined as:

$$k_b = k_{b0}\left(\frac{\varphi_b}{\varphi_{b0}}\right)^3 \tag{2.4}$$

k_{b0}—— The initial permeability of coal matrix; k_b is the coal matrix permeability.

Substitute equation (2.1) into equation (2.4) to obtain:

$$k_b = k_{b0}\left(\frac{1}{(1+Q)}\left[(1+Q_0) + \frac{\alpha_b(Q-Q_0)}{\varphi_{b0}}\right]\right)^3 \tag{2.5}$$

As can be seen from the definition:

$$\frac{\varphi_f}{\varphi_{f0}} = 1 + \frac{\Delta b}{b} \tag{2.6}$$

The porosity of the fracture can be deduced:

$$\frac{\varphi_f}{\varphi_{f0}} = 1 + \frac{\Delta b}{b} = \left[1 - \frac{3}{\varphi_{f0} + \frac{3L_f}{K}}\left(\frac{\varepsilon_L \Delta P_b}{P_L + \Delta P_b} - \varepsilon_V\right)\right] \tag{2.7}$$

L_f ——the improved fracture stiffness, Pa;

ΔP_b——gas pressure change of coal matrix, Pa.

The relationship between the known coal fracture permeability and fracture porosity is as follows:

$$k_f = k_{f0}\left(\frac{\varphi_f}{\varphi_{f0}}\right)^3 \tag{2.8}$$

The Klinkenberg effect can be obtained by substituting equation (2.7) into equation (2.8) :

$$k_f = k_{f0}\left(1 - \frac{3}{\varphi_{f0} + \frac{3L_f}{K}}\left(\frac{\varepsilon_L \Delta P_b}{P_L + \Delta P_b} - \varepsilon_V\right)\right)^3 \left(1 + \frac{c}{P_f}\right) \tag{2.9}$$

c ——the Klinkenberg coefficient, $c = 0.95k_f - 0.33$;

P_f ——the gas pressure in the coal fracture, Pa.

2.3.2 Gas Diffusion Equation

The gas occurrence in coal seam is usually in a dynamic leveling process, and the pressure of gas adsorption by matrix is equal to the pressure of free gas in the fracture. Since the pressure of gas adsorption by matrix is difficult to be determined, it is generally considered that the pressure of gas adsorption is equal to the pressure of gas in the fracture under the corresponding hypothetical equilibrium.

(1) The diffusion equation of matrix gas

The existence forms of gas in coal matrix include adsorption gas and free gas, so the gas mass m per unit volume of coal matrix can be calculated by Langmuir equation:

$$m = \rho_b \varphi_b + \rho_g \rho_c \frac{V_L P_b}{P_L + P_b} \tag{2.10}$$

ρ_b ——the gas density of coal matrix, kg/m^3;

ρ_g ——the gas density under standard conditions, kg/m^3;

ρ_c ——the coal skeleton density, kg/m^3;

V_L ——the Langmuir volume, kg/m^3.

The results show that the free gas in the fracture transmits pore pressure, and the adsorption gas does not produce this effect. When using borehole drainage, the original coal gas pressure balance is broken, due to the fracture and seepage velocity of different pore system, adsorption gas pressure will be bigger than the fracture free gas pressure, substrate by diffusion into the fracture after gas desorption, therefore between the matrix and fracture of coal gas quality switched to:

$$D_m = \frac{M_g d_0}{\tau RT}\left(P_b - P_f\right) \tag{2.11}$$

According to the law of mass conservation:

$$\frac{\partial m}{\partial t} = -D_m \tag{2.12}$$

According to the law of gas migration, the law of mass conservation and considering the influence of gas drainage, the following can be obtained:

$$\frac{\partial}{\partial_t}\left(\frac{V_L P_b}{P_L + P_b}\frac{M_g}{RT}\rho_s P_s\right) + \frac{\partial}{\partial_t}\left(\varphi_b \frac{M_g}{RT} P_b\right) + \nabla \cdot \left(-P_b \frac{M_g k_b d_0}{\mu RT}\nabla P_b\right) = \frac{M_g d_0}{\tau RT}\left(P_f - P_b\right) \tag{2.13}$$

τ ——gas desorption time, s;

M_g ——the molar mass of gas, kg/mol;

R——the molar constant of gas, $J/(mol \cdot K)$;

T——coal seam temperature, K;

μ——gas dynamic viscosity P_a;

ρ_s——the coal matrix density, kg/m^3;

P_s——standard atmospheric pressure, Pa;

∇ ——Hamiltonian operator.

(2) The seepage equation of fracture gas:

The free gas occurs in the fracture. It can be seen that the gas velocity q in the coal fracture is:

$$q = -\frac{k_f}{\mu}\nabla P_f \tag{2.14}$$

Then, the gas transport equation in the crack can be obtained as follows:

$$\frac{\partial}{\partial_t}\left(\varphi_f \frac{M_g}{RT} P_f\right) + \nabla \cdot \left(-\frac{M_g k_f}{\mu RT}\nabla P_f\right) = \left(1-\varphi_f\right)\frac{M_g}{\tau RT}\left(P_b - P_f\right) \tag{2.15}$$

(3) The stress field equation:

Based on the hypothesis above, the total strain of coal is caused by the combined action of strain caused by stress, strain caused by fluid and strain caused by gas desorption. Therefore, the stress-strain relationship of coal and rock mass can be obtained as follows:

$$Gu_{i,ij} + \frac{G}{1-2v}\varepsilon_v - \alpha_f P_f - \alpha_b P_b - \sigma_a + F_i = 0 \tag{2.16}$$

G ——the shear modulus of coal containing gas, MPa;

ε_v—— the volumetric strain; F sub I is the volume force, MPa.

According to the permeability model, the variation of gas pressure (matrix gas pressure P_b and fracture gas pressure P_f) is related to permeability.

According to the coupling model, the dynamic change of matrix permeability k_b and fracture permeability k_f respectively depends on the dynamic change of coal matrix porosity k_b and fracture porosity k_f. With the development of gas drainage, due to the decrease of gas pressure, the effective stress increases, the coal skeleton compresses, and the coal matrix shrinks, resulting in the porosity of the coal matrix φ_b, and the porosity of the crack φ_f accordingly changes. In addition, the change of fracture permeability k_f is not only affected by the porosity of the fracture φ_f, but also by the change of the gas pressure P_f.

The gas movement in coal body includes two kinds of movement: diffusion and seepage. The gas in the matrix takes part in the seepage after desorption and diffusion, and the seepage result after being affected affects the mass transfer rate of the coal matrix in reverse, which are boundary conditions of each other. Therefore, the mass exchange from diffusion field to seepage field is called positive mass source, while the mass exchange from seepage field to difusion field is called negative mass source. According to the principle of effective stress in dual media, the gas migration field has a certain influence on the deformation field of coal body. When the gas pressure balance in coal body is broken, the pressure gradient can be equivalent to the volume force.

In summary, above model constitute the gas-solid coupling model of gas seepage with dual-pores and dual- permeability considering the Klinkenberg effect, desorption-diffusion effect, coal skeleton compression effect and matrix contraction effect.

3 Numerical Simulation Study on Solid Gas Coupling in Gas Drainage from Single Borehole along the Bedding

In the field of physical science and engineering, the analysis of solid stress and strain and fluid motion can be solved by partial differential equation or ordinary differential equation under specific boundary conditions. However, for most engineering problems, due to the complexity of the boundary conditions of the nonlinear features, the solution obtained by the available analytical methods cannot reach the ideal accuracy. Therefore, the numerical simulation method can only be used to solve the problem by using numerical simulation software and related technology. In this paper, the COMSOL Multiphysics is used to build the geometric model of gas drainage in single borehole along the bedding layer, and the solid-gas coupling model of gas drainage in single borehole along the bedding layer is studied by combining the characteristics of gas seepage in the coal seam.

3.1 Model Building

3.1.1 Geometric Modeling

In this chapter, the gas drainage model is simulated by single borehole along the bedding. The two-dimensional simplified horizontal profile of coal seam is selected and model grid division, as shown in Fig.3.1 and Fig.3.2. The geometric model parameters are: the height of coal seam W=5m, the length L=50m; The diameter of the borehole is d=100mm, the borehole is located in the center of the model, and an observation point is set 5m away from the drainage borehole.

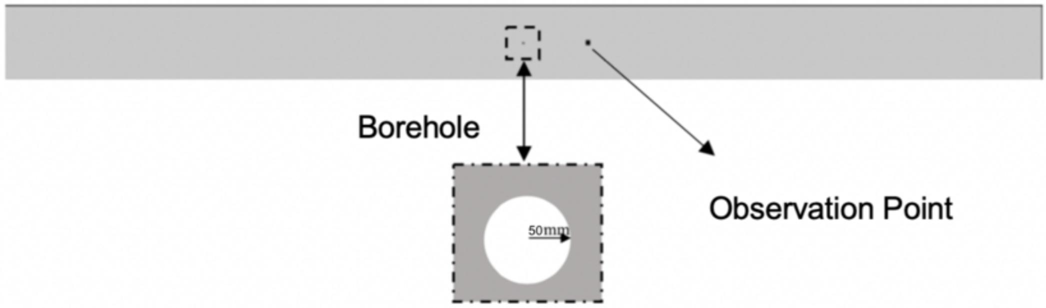


Fig.3.1Two-dimensional geometric model

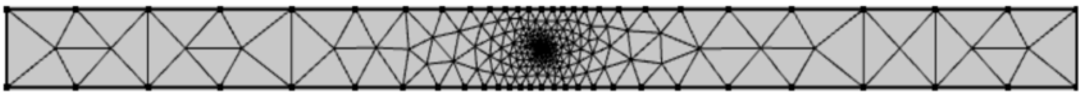


Fig.3.2 Model meshing

3.1.2 Simulation Parameter Selection

Tab.3.1 Selected model parameters

Parameter	Value
Initial maxtrix porosity φ_{b0}	0.06
Initial fracture porosity φ_{f0}	0.012
Initial matrix permeability k_{b0}/mD	5×10^{-19}
Initial fracture permeability k_{f0}/mD	1×10^{-18}
Crack width b/m	0.005
Matrix width a/m	0.002
Coal seam temperatureT/K	315.15
Desorption timeτ/s	794880
Drainage negative pressure P_b/MPa	0.123
Langmuir pressure $P_L/M\mathrm{Pa}$	1

Continue Tab.3.1

Langmuir volume $V_L/m^3 \cdot t^{-1}$	0.018
Strain constant ε_L	0.008
Poisson's ration v	0.35
gas Dynamic viscosity $\mu/Pa \cdot s$	1.03×10^{-5}
Coal skeleton density $\rho_c/(kg \cdot m^{-3})$	1.4×10^{-3}
Decay coefficient λ/s^{-1}	1×10^{-17}
Initial diffusion coefficient $d_0/m^2 \cdot s^{-1}$	5.48×10^{-12}
Coal seam gas pressure P_0/MPa	2

3.1.3 Initial Boundary Condition Setting

Tab.3.2 Condition setting of gas seepage field equation

Condition type	Calculation region	value
Initial condition	Entire region	2 MPa
Dirichlet boundary	Borehole boundary	Normal atmospheric pressure/negative pressure (20kPa)
Neumann boundary *	Coal seam boundary	Pg=0

Tab.3.3 Condition setting of gas diffusion equation

Condition type	Calculation region	value
Initial condition	Entire region	6.73m^3/t
Dirichlet condition	Borehole boundary	0.21m^3/t
Neumann condition*	Coal seam boundary	$\Delta V_a=0$

Tab.3.4 Condition setting of stress equation

Region	Setting conditions
Coal seam bottom	Fixed constraint
Coal seam top	Constant load（20MPa）
Both sides of coal seam	Roller supporting

3.2 Analysis on Influencing Factors of Gas Drainage by Borehole in Bedding

The factors affecting gas drainage along the bedding borehole include: drainage time and negative pressure of drainage, borehole diameter, etc. The purpose of this chapter is to discuss the influence of the above factors on gas drainage, so as to provide a scientific basis for rational gas drainage by bedding borehole.

3.2.1 Drainage Time

According to the gas migration model of in gas drainage process established in chapter 2, combined with the geometric model and boundary conditions built in this chapter, this section will apply the above conditions and contents to simulate the gas drainage process of model coal seam for 600d, and analyze the relationship between permeability and gas pressure.

1) Gas pressure:

(1) The difference between matrix gas pressure and fracture gas pressure

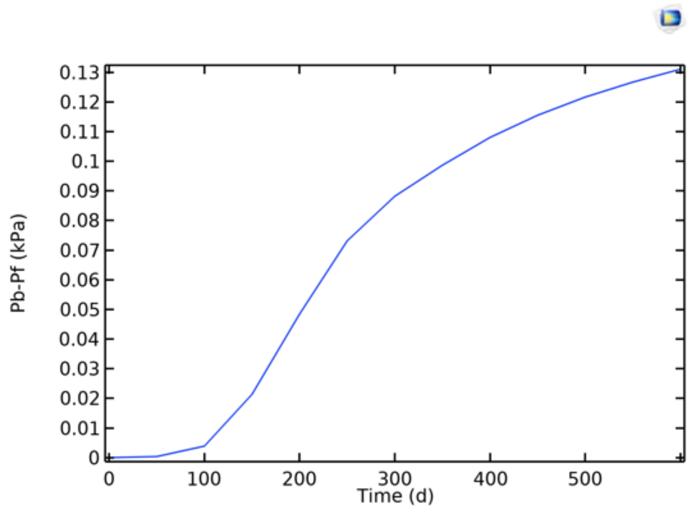
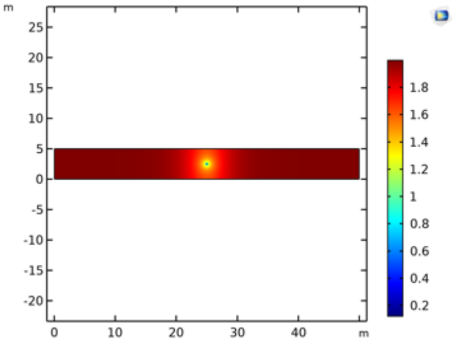


Fig.3.3 The difference between matrix gas pressure and fracture gas pressure

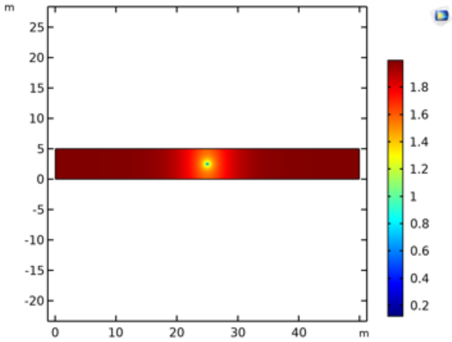
According to the Fig.3.3 shows that in the process of gas drainage, the changes of fracture gas pressure and gas pressure matrix. 100 days ago, the difference of the two basic is zero, and drainage to 100 days later, the gas pressure is smaller than the matrix gas pressure. This is because under the effect of drainage, the fracture gas seepage into the drilling rate faster, by gas pressure drop trend is more obvious, seepage and diffusion of gas pressure and matrix effect compared with crack gas pressure is not obvious, so the matrix gas pressure is bigger. But on the whole, the gap is not large, biggest difference just 1.3 kPa, therefore can be regarded as basic consistent. The gas pressure is represented by P as follows

(2) Change law of gas pressure：

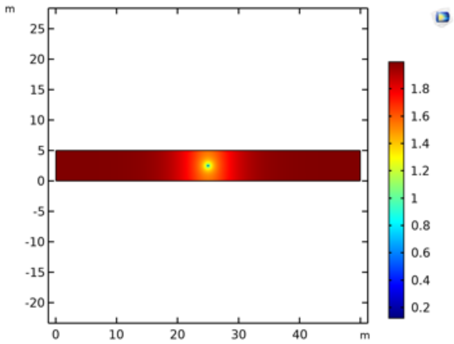
The change of gas pressure can be used as a characteristic factor of gas flow and an important evaluation parameter in the actual process of gas drainage. Fig.3.4 presents the cloud diagram of gas pressure changes under the condition of negative drainage pressure of 20kPa.



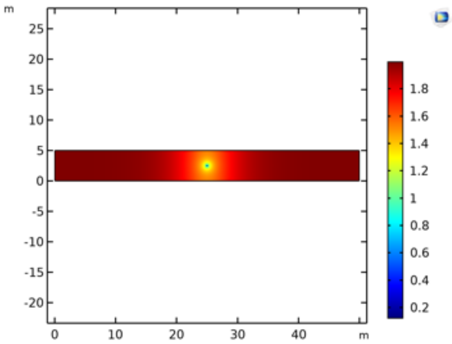
(a) t=150d



(b) t=300d



(c) t=450d



(d) t=600

Fig.3.4 Gas pressure cloud image of matrix pores

As can be seen from Fig.3.4, with the increasing of pumping time, the effective drainage area is increasing. As can be seen from Fig.3.5 and Fig.3.6, the matrix gas at the observation point decreases continuously with the gas drainage time. In the initial stage of gas drainage, the gas pressure in the pores around the borehole decreases at a higher rate. This is because the observation point is close to the borehole center, so the gas pressure in this area is much less than that in the region far away from the borehole, namely a large gas gradient occurs between the near borehole area and far away from the borehole area, to produce the large gas pressure difference. Therefore, the desorption rate of gas near the borehole is greater than that of the area not affected by drainage. This not only replenishes the fracture gas near the observation point, but also speeds up the seepage action of the fracture. The gas pressure at the observation point decreases rapidly in the early stage of gas drainage. With the ongoing of gas drainage, the gas pressure gradient gradually increases between the observation point and the area far away from the borehole.

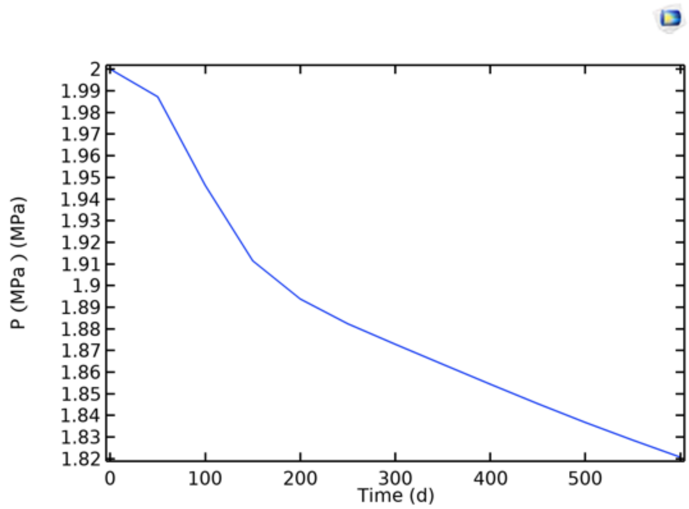


Fig.3.5 Variation curve of matrix gas pressure at the observation point with time

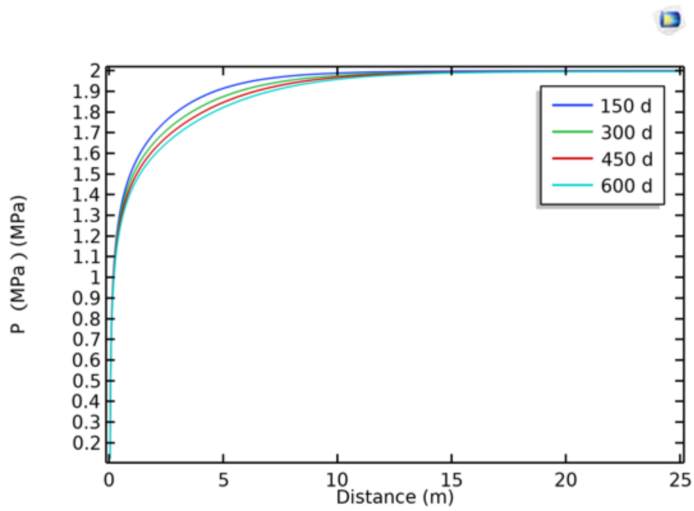


Fig.3.6 Distribution of matrix gas pressure at different drainage time

2) Change law of permeability

Permeability is often used as the evaluation standard of gas seepage capacity because it is related to many physical parameters of coal seam, and fracture permeability is the main influence on gas migration rate during gas drainage. To a certain extent, permeability reflects the degree of a fracture connectivity, which affect the process of gas drainage. The gas migration from the matrix to the fracture is dominated by diffusion, with little influence of seepage. Therefore, this section focuses on the change law of coal fracture permeability k_f.

(1) The Variation Law of Fracture Permeability with Gas Pressure

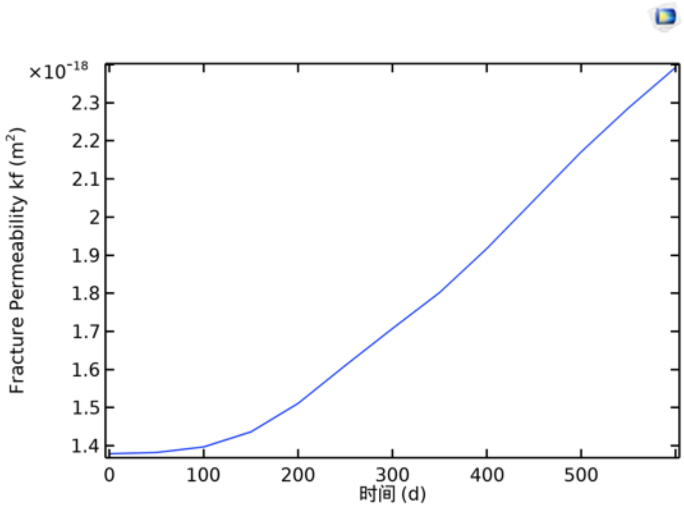


Fig.3.7 Variation curve of fracture permeability with gas pressure at the observation point

According to Fig. 3.7 and Fig.3.8, it can be seen that at the observation point, the influence of gas pressure on fracture permeability k_f is very obvious. The permeability increases with the increase of drainage time, that is, with the decrease of gas pressure.

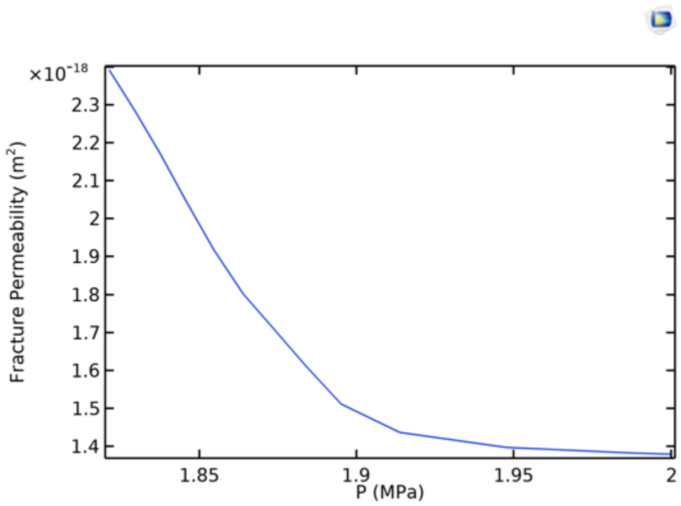


Fig.3.8 Curve of fracture permeability with fracture porosity at the observation point

It can be seen from Fig. 3.9 that the permeability in the area near the borehole is larger than that in the area far away from the borehole. This is because the area near the borehole is affected by gas drainage, which leads to changes in the structure of the coal body and increases the connectivity degree of the coal body fractures near the borehole, thus increasing the permeability.

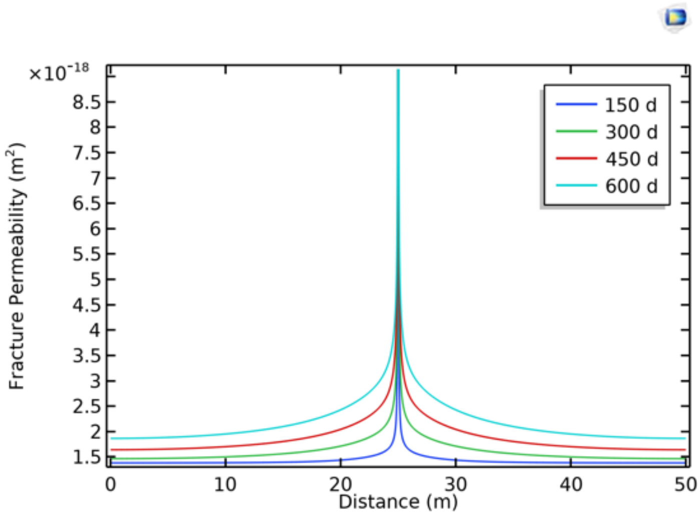


Fig.3.9 Permeability distribution at different drainage time

From the above analysis, it can be seen that with the increase of drainage time, the gas pressure of coal body decreases and the permeability increases.

3.2.2 Drainage Negative Pressure

In this section, different drainage negative pressures (10kPa, 20kPa and 30kPa) are set to simulate gas drainage under the condition of 100mm borehole diameter along the bedding for 600d, and other parameters are kept unchanged. The purpose is to analyze the change rules of coal seam gas pressure and fracture permeability. Fig.3.10 shows the gas pressure distribution diagram of gas drainage from borehole along the bedding under different negative drainage pressures. Fig.3.11 shows the distribution of permeability of coal under different drainage negative pressure.

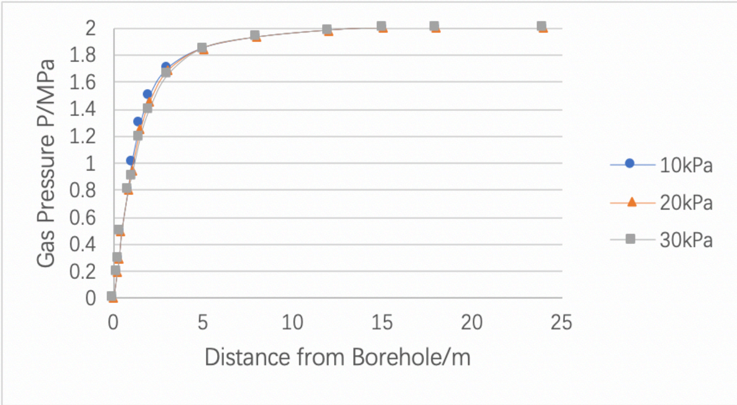


Fig.3.10 Distribution of gas pressure under different drainage negative pressure

As can be seen from Fig. 3.10, after continuous drainage for 600d, there is no obvious difference in coal seam gas pressure under different drainage negative pressures. When the negative pressure of borehole drainage along the bedding increases from 10kPa to 30kPa, the gas pressure near the borehole decreases slightly, especially in the area close to the borehole (0-8m). However, the gas pressure far away from the borehole does not change with the change of the negative drainage pressure of drainage. It also can be seen from Fig.3.11 that the permeability is basically unchanged under different drainage negative pressure.

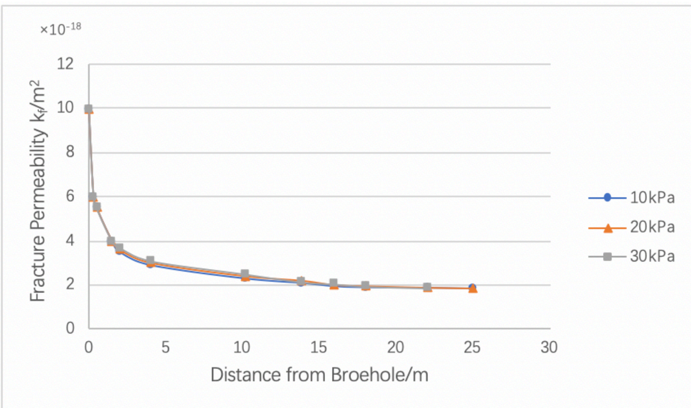


Fig.3.11 Permeability distribution under different drainage negative pressure

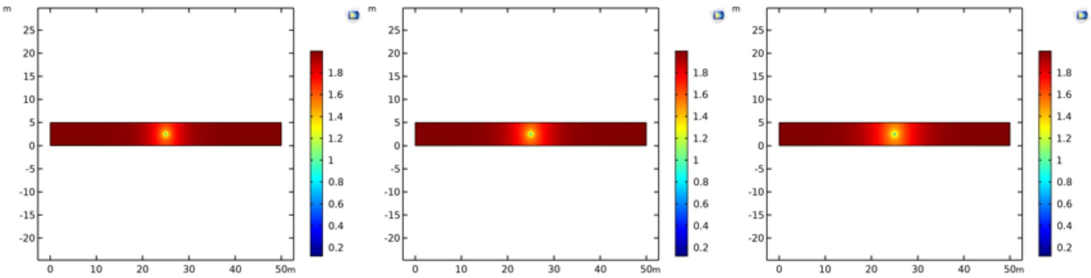
To sum up, it can be concluded that; The influence of negative drainage pressure on gas drainage from coal seam by drilling is very limited, and the fracture permeability of coal seam are not significant. Therefore, it is of little significance to change the drainage effect by changing the negative pressure of drainage. According to previous studies, the negative pressure of drainage is not easy to be too large, otherwise it will cause the gas flow rate in the drainage tube is too large, making the gas flow along the resistance is also increased, and then lead to the temperature rise of drainage tube, easy to cause combustion, so it should be selected in the gas drainage project appropriate negative pressure.

3.2.3 Borehole Diameter

Based on the research purpose and the demand of numerical simulation, this section still takes the gas drainage with single borehole along the bedding as the model. The simplified horizontal profile with two-dimensions of coal seam is selected. The parameters of the geometric model are: length of coal seam L = 50m, height H = 5m; The borehole is located at the center of the model. The boreholes of 80mm, 100mm and 120mm are selected to simulate the drainage effect at different time (150d, 300d and 600d) when gas drainage is carried out in the horizontal borehole under the given conditions of negative drainage pressure (20kPa). The initial gas pressure is set to 2MPa in this section.

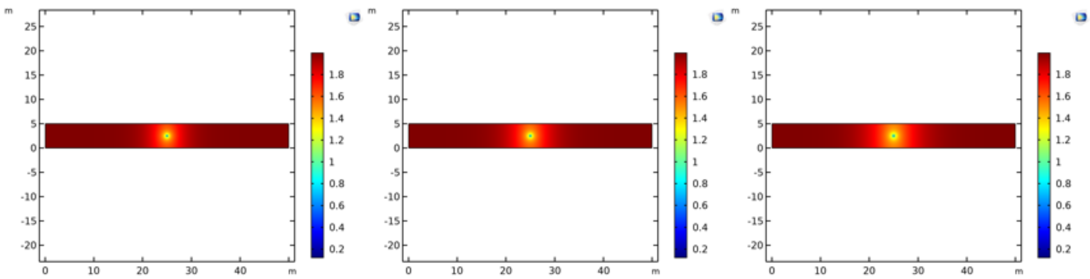
1) Gas pressure

In this chapter, the gas drainage process of boreholes with different drainage times of 80mm, 100mm and 120mm is simulated. According to the simulation results, the gas pressure variation and distribution of drainage times of 150d, 300d and 600d can be derived, as shown in Fig. 3.12, Fig.3.13 and Fig.3.14.



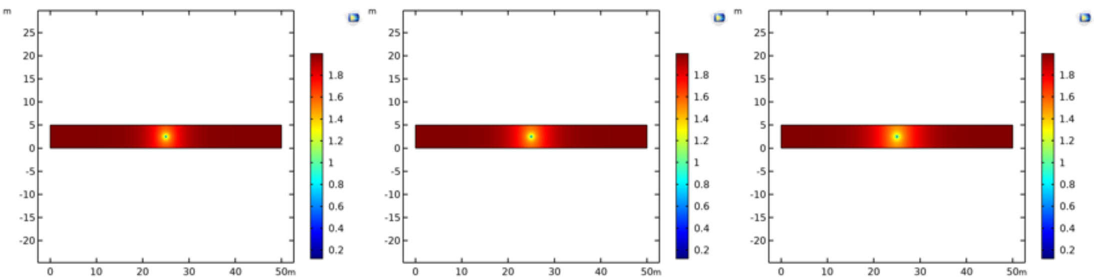
(a) t=150d **(b) t=300d** **(c) t=600d**

Fig.3.12 Contour map of gas pressure distribution at borehole aperture of 80mm



(a) t=150d **(b) t=300d** **(c) t=600d**

Fig.3.13 Contour map of gas pressure distribution at borehole aperture of 100mm



(a) t=150d **(b) t=300d** **(c) t=600d**

Fig.3.14 Contour map of gas pressure distribution at borehole aperture of 120mm

According to Fig.3.12, Fig.3.13 and Fig.3.14, no matter what kind of borehole diameter, the effective radius of drainage increases with the increase of time.

In order to more intuitively show the influence of borehole diameter on the drainage process, the gas pressure distribution curve was compared. As shown in Fig.3.15, When the borehole diameter is 80mm, the effective drainage radius should be significantly smaller than the borehole diameter of 100mm and 120mm. The gas drainage radius under the condition of 120mm drilling diameter is slightly larger than 100mm but the difference of effective drainage radius is not obvious. It can be seen that the borehole diameter has a certain influence on the drainage, that is, it increases with the increase of the borehole diameter, but when it increases to a certain range, the influence effect gradually weakens.

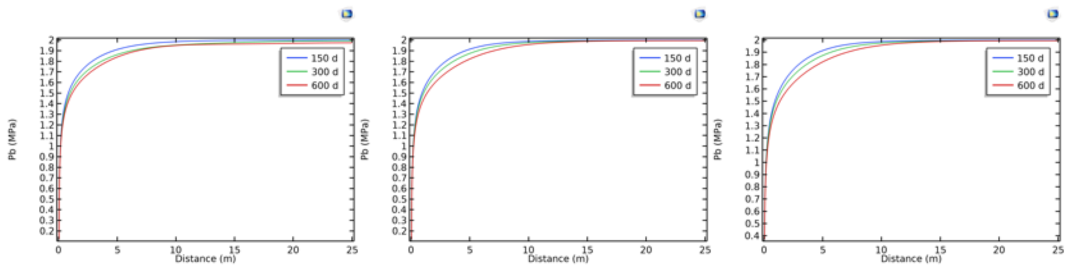


Fig.3.15 Variation curve of gas pressure with time at different apertures

2) Change law of proportional coefficient of coal permeability

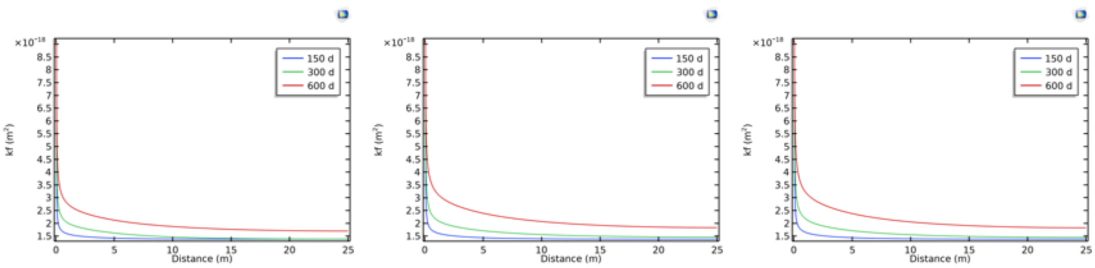


Fig.3.16 Variation curve of permeability with time at different aperture

As shown in the Fig.3.16, the permeability is a key parameter that affects gas migration. The higher the permeability is, the better the drainage effect will be. It can be seen from the Figure that, under the same drainage time, the larger the borehole diameter is, the larger the permeability will be. Combined with

Figure 3.15, it can be seen that under the condition of high permeability, the corresponding gas drainage radius is larger, so the gas drainage effect is also better.

4 Numerical simulation of gas drainage with double boreholes along the bedding

4.1 Modeling

4.1.1 Geometric Modeling

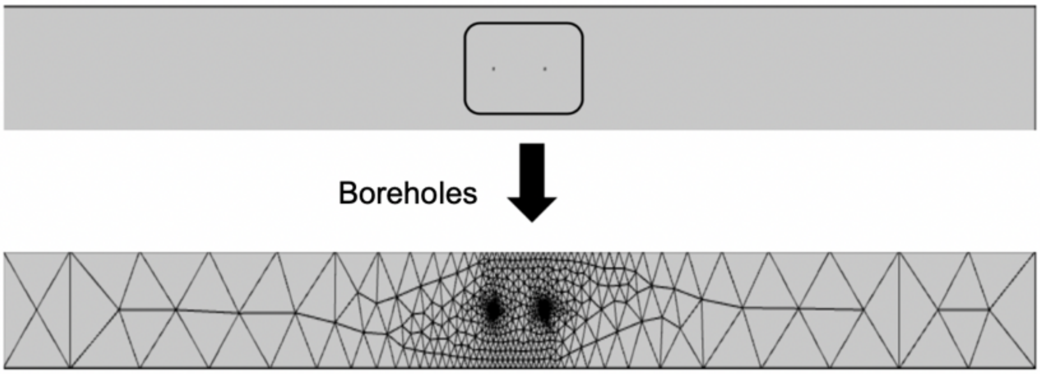


Fig.4.1 Geometric partition model

The geometric model is derived from the reasonable simplification of the engineering practice of pre-drainage and elimination of outburst in the low-permeability coal seam by using bedding borehole drainage. The geometric model parameters are: the height of coal seam W = 5m, the length L = 50m; The diameter of the borehole was d = 100mm, and gas drainage simulation was conducted for different borehole distances (2m, 5m, 10m and 15m) respectively.

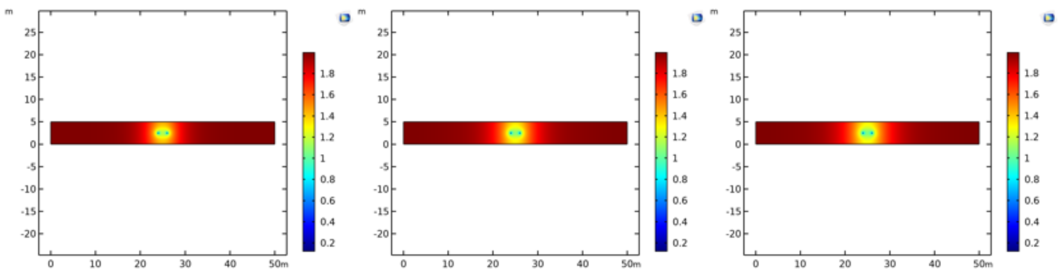
4.1.2 Simulation Parameter and Condition Setting

In third chapter, the gas drainage model with single borehole is built based on dual-pore and dual-permeability. The simulation parameters set during the simulation process are based on field data collection, reference to relevant data standards and project reports. All parameters of this section are referred to in Tab.3.1

4.2 Simulation Results Analysis

Based on the solid-gas coupling model with dual-pore and two-permeability built above, this section will use it to carry out the numerical simulation of gas drainage along the bedding of 100mm double boreholes, carry out the simulation of gas drainage of the set target coal seam for 600d, and mainly select typical indicators， including gas pressure and permeability, to analyze the simulation results. Based on the simulation results, the influence of different hole spacing on each typical index in gas drainage process is discussed.

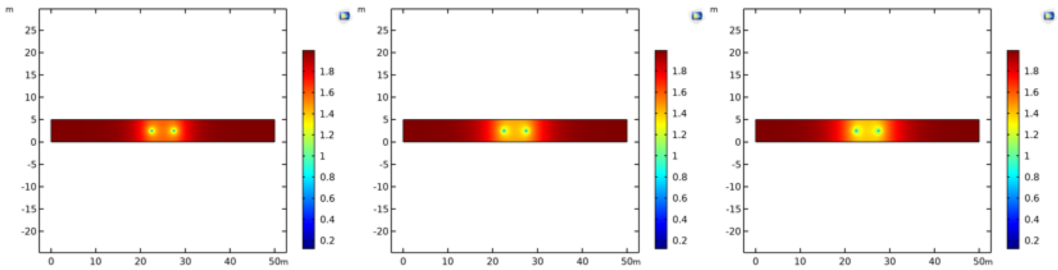
1) Gas pressure



(a) t=150d **(b) t=300d** **(c) t=600d**

Fig.4.2 Gas pressure distribution cloud map with borehole spacing 2m

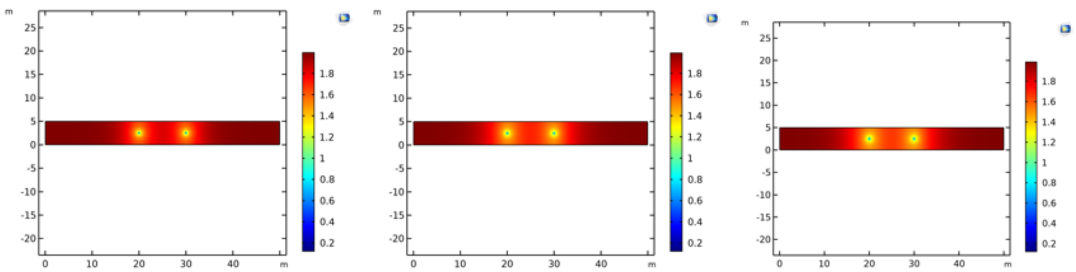
As shown in Fig.4.2, When the borehole spacing is 2m, an obvious low-pressure area of gas appears between two boreholes, and the drainage effect of these two boreholes is similar to that of single borehole drainage, namely, the effective area of drainage is small.



(a) t=150d **(b) t=300d** **(c) t=600d**

Fig4.3 Gas pressure distribution cloud map with borehole spacing 5m

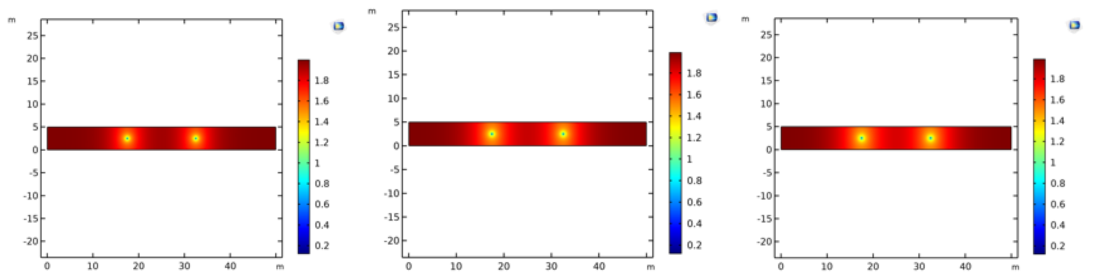
According to Fig.4.3, When the hole spacing is 5m, it is similar to that when the hole spacing is 2m, and an obvious low-pressure area of gas is also generated between the boreholes, but the effective radius of drainage is obviously greater than that when the borehole spacing is 2m.



(a) t=150d **(b) t=300d** **(c) t=600d**

Fig.4.4 Gas pressure distribution cloud map with borehole spacing 10m

As shown in Fig. 4.4, when the borehole spacing is 10m, there is still a gas low pressure area between the two boreholes, but the pressure difference between the low-pressure area of gas and other areas is less than that between 2m and 5m. The effective area of drainage is significantly larger, indicating that the drainage effect is the best among the three boreholes spacing arrangements.



(a) t=150d (b) t=300d (c) t=600d

Fig.4.5 Gas pressure distribution cloud map with borehole spacing 15m

It can be seen from Figure 4.5 that under the condition of borehole spacing of 15 meters, the low-pressure area of gas between two boreholes is completely not obvious, that is, there is a blind zone of drainage, resulting in the overall drainage effect is not as good as the first three cases.

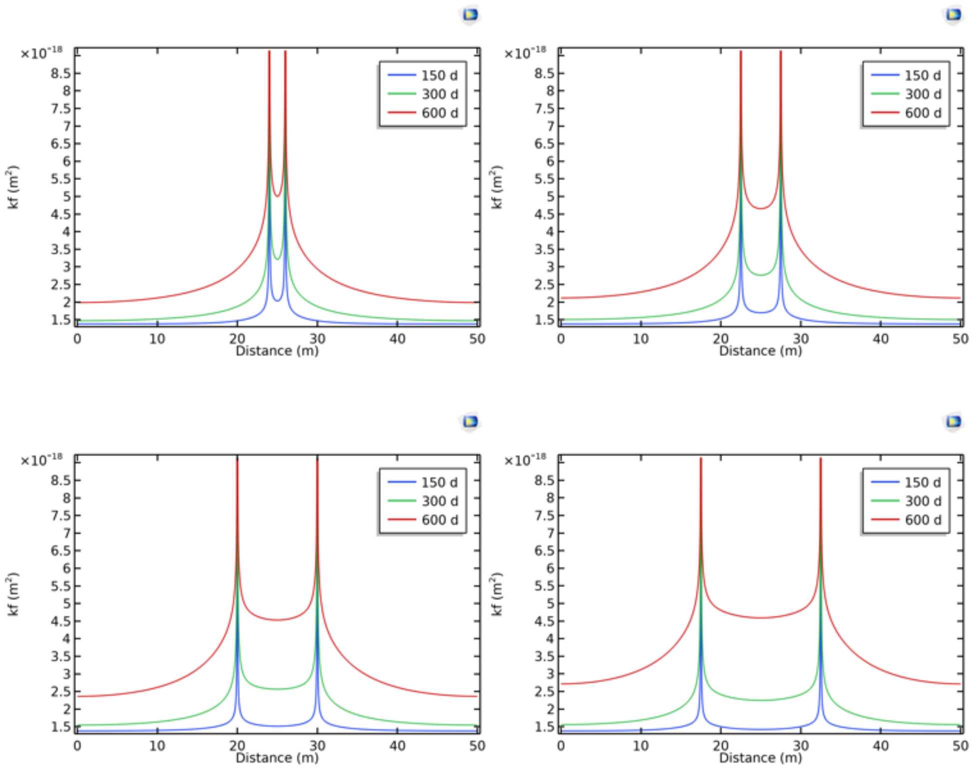


Fig.4.6 Variation curve of fracture permeability with different borehole spacing

According to the gas pressure distribution curve, the relationship between gas pressure and hole spacing is discussed. The Figure 4.6 shows that in the early stage of the drainage, the permeability of the outside of the borehole is very similar under the four kinds of borehole layouts. And the permeability of borehole spacing arrangement by day 600, all kinds appeares more obvious differences. The lateral permeability is only 2×10^{-18} $m^2$when the borehole spacing is 2 meters. The borehole spacing for 5 meters and 10 meters, the borehole of the lateral permeability relatively close, between 2×10^{-18}~2.5×10^{-18} m^2, and borehole spacing of 15 meters, the lateral permeability is greater than the first three hole spacing arrangement. It can be seen from the above that the greater the permeability is, the more favorable it will be for gas drainage and the better the drainage effect will be. Therefore, when the hole spacing is greater than 2m, the more favorable it will be for gas drainage. However, the effect of gas drainage is not completely dependent on the permeability, but also needs to be analyzed according to the actual situation.

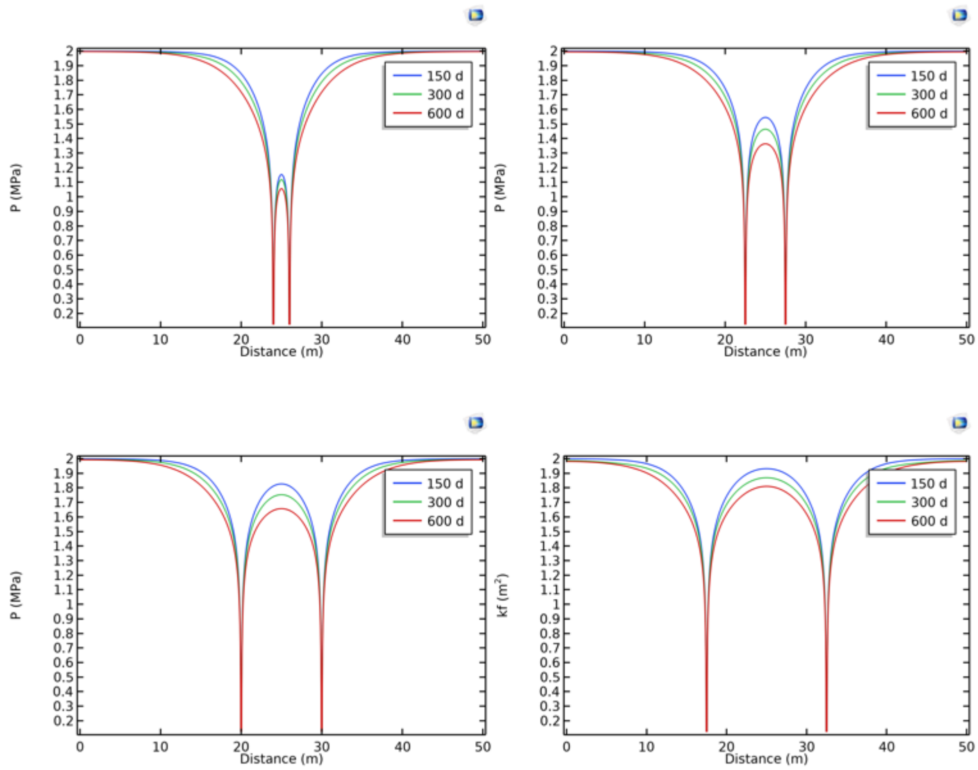


Fig.4.7 Distribution of gas pressure with different borehole spacing

It can be seen from FIG. 4.7 that, when the borehole spacing is 2 meters, there is an obvious pressure drop between the boreholes, but the impact on the outside of the borehole is very limited. The effective area of gas drainage is overlapped, which is more similar to the case of single borehole, and its impact on the whole coal seam is relatively limited. However, when the borehole spacing is 15 meters, there is a blind spot. The gas pressure between boreholes does not show an obvious downward trend, which only affects local areas. Therefore, when the borehole spacing is large, the drainage effect is very limited. It is worth noting that when the borehole spacing is between 5 meters and 10 meters, the gas pressure between boreholes not only drops obviously, but the effective drainage radius is also relatively obvious. It can be seen that when the boreholes spacing is between 5 meters and 10 meters, it has a relatively obvious effect on the gas drainage of the entire coal seam, and the gas pressure drops more obviously.

5 Conclusion

In order to study gas seepage of coal seam based on solid-gas coupling, this paper mainly develops the gas seepage law with dual-pore and dual-permeability based on the solid-gas coupling model by modeling, verifying the experimental data and combining with the numerical simulation method, and using COMSOL Multipysics platform to study the result of the simulation.

The conclusions are as follows:

(1) The gas migration state in coal seam is highly correlated with the pore structure of coal seam, while the coal structure in nature is complex and changeable. In the process of gas drainage and mining, the movement of gas includes diffusion and seepage, and the adsorbed gas in the matrix is desorbed and diffused and then involved in the seepage, both of which are the mass sources of gas of the seepage field, and the change of the seepage also has a certain influence on the diffusion of the coal matrix gas.

(2) In the whole drainage project, the value of matrix gas pressure and crack gas pressure does not differ much, and the maximum difference between them is not more than 1.3kPa. This is because of the difficulty of early drainage, gas desorption diffusion and seepage velocity are slow, so the difference is 0. The difference between the two is basically zero in the early stage, but gradually increases in the later stage. In the later stage, due to the influence of gas drainage, the structure of coal body changes, resulting in the difference between seepage velocity and desorption diffusion velocity, resulting in the difference between them.

(3) The permeability of coal is an important indicator to measure the gas drainage effect. Through the simulation of gas drainage by single bedding borehole, the gas pressure decreases with the increase of drainage time, and

the change of permeability is just the opposite. This is because as the drainage from ongoing, less force of coal seam gas continuously decreases. Under the influence of drainage effect lead to coal deformation and coal matrix shrinkage, produced more fracture and the increased connectivity, resulting in permeability of coal is increasing.

(4) The early stage of the gas pressure drop is fast because of its high gas content of coal seam, seepage gas, mostly so the effective gas drainage rate is higher. Late due to the seepage quantity of gas is reduced, most of the gas from coal gas adsorption and desorption from matrix, the process is relatively slow, so the effective gas drainage rate is decreased.

(5) The process of gas drainage is influenced by multiple physical parameters. In this paper, the gas drainage process under different negative pressure conditions is simulated. According to the result of simulation, it can be known that the influence of the negative pressure of drainage on the gas drainage is very small. When adopting different negative pressure of drainage, coal seam gas pressure, there is no obvious change in the porosity and effective permeability.

(6) Different borehole sizes are used to simulate the process of gas drainage based on the dual-pore and dual-permeability model, and the choice of pore size has a great influence on the drainage process. When 80mm diameter of borehole is used, the gas pressure decline rate is obviously less than 100mm and 120mm. Under the same drainage time, the larger the borehole diameter is, the larger the permeability will be and the corresponding gas drainage radius is larger, so the gas drainage effect is also better.

(7) Different borehole spacing leads to inconsistent gas drainage effect. When the boreholes spacing is closer, the effective drainage of borehole drainage occurs overlap. When the spacing of borehole layout is too large, there will be blind area of drainage, which is not conducive to drainage, all of which lead to effective each borehole drainage area is limited. When

reasonable borehole spacing, borehole drainage affect regional distribution is uniform and the gas pressure of coal seam drops significantly. Therefore, it is of great significance to choose reasonable spacing of boreholes for gas drainage.

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Thesis Grade

Thesis: Numerical Simulation of Coal-Seam Gas Drainage Based on Solid-Gas Coupling Model

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