Comparative Analysis of the Drainage Effect Based on Improved Hydraulic Flushing Technology

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ABSTRACT: The composite structure coal seam composed of coal seams with strong and weak deformation is widely developed in the coalfields in Southwest and North China. The implementation of hydraulic flushing in soft coal stratification can effectively relieve the pressure and increase the permeability of coal seams, so it can improve the effect of underground gas drainage. Taking Xin’an Coal Mine, West Henan province, China, as an example, this paper discussed the influence of hydraulic flushing on the gas drainage effect in soft coal seam by means of field investigation, numerical simulation analysis, similar simulation, and field verification. As the same time, a fluid–solid coupling model of gas drainage based on layered hydraulic flushing technology is established, and the differences and reasons of the gas drainage effect after layered hydraulic flushing in soft and hard composite coal seams are discussed. The results show that (1) the gas concentration change of layered flushing boreholes intermittently rises rapidly, and there is no obvious law, while that of conventional flushing boreholes shows a regular attenuation trend. (2) According to the numerical simulation results, after 30 days of drainage, the effective drainage range of layered hydraulic flushing is 8.33 m³ higher than that of conventional hydraulic flushing. (3) There are not a few points where the single borehole concentration data of each row of layered flushing boreholes are in the high level. Meanwhile, the maximum concentration of all conventional flushing boreholes is less than 40%, except that one borehole can reach 70% at the beginning. (4) All of the average gas drainage concentration of single-row boreholes using layered flushing technology is greater than 20% in the vast majority of days, while that of the conventional flushing boreholes is only higher than 20% in row 5 and has only lasted for 2 days. The difference of the drainage effect is obvious.

1. INTRODUCTION

Unlike abroad, the coal-bearing strata in China experienced several tectonic movements after their formation. Therefore, soft coal seams with high tectonic stress, low strength, and low permeability widely develop.1 What is worse, with the shallow coal resources exhausting, the coal mining depth continues to increase at a rate of about 20 m per year in China. With the gradual deep mining of coal mines in China, coal seams are increasingly characterized by high stress, high gas content, and high pressure. Such many unfavorable features of coalbed methane occurrence conditions restrict the efficient exploitation of coalbed methane resources in China,2−5 which also bring the risk of coal and gas outburst accidents, especially in a soft coal stratified development area.5−9

Mine gas is also a kind of clean energy and greenhouse gas, which will not only waste resources but also cause environmental pollution if not utilized.10,11 Therefore, it is necessary to control coal seam gas. Research shows that the extraction of coal seam gas can reduce the gas content and pressure of coal seam, reduce the possibility of coal and gas outburst and other disasters, and ensure the personal safety of underground workers; the use of extracted gas can increase the utilization rate of resources, reduce greenhouse gas emissions, and protect the atmospheric environment.12−15

Therefore, it is urgent to improve the efficiency of gas drainage. Based on this background, many scholars have carried out relevant research to solve the problem16−18 and numerous methods have been applied to improve the permeability of coal seams, such as microbial technologies,19 received: September 12, 2022
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explosive blasting prefracturing, CO₂ phase transition, gas displacement, microwave radiation, and acoustic excitation technology. However, because of the great limitations and high cost, these methods cannot be widely used.

Compared with the above methods, protective layer mining technology was once considered to be the most economical and effective method for gas drainage in coal mines. The China State Administration of Work Safety stresses that the protective coal layer should be mined first when a coal seam group is present. The technology aims to mine a coal seam with low gas outburst risk so as to relieve the stress and improve the permeability in the protected coal seam. The protective layer can be divided into coal seam and rock strata according to different lithology. According to the position of the protective layer, it can be regarded as a upper protective layer, lower protective layer, and upper protective layer and lower protective layer at the same time. The mining technology of the protective layer has been greatly recognized in practical engineering, but unfortunately, many coal seams in China that face the risk of coal and gas outburst do not have proper protective coal seam. Although the soft rock strata can be a protective layer for mining in some coal mines, the thickness of a single rock layer may not meet the needs of protective layer mining. This indicates that despite the fact that the mining of the protective layer is economical and effective, it is greatly limited by geological conditions.

In addition to the protective layer mining technology, the advantages of hydraulic measures are also gradually highlighted. The broken coal mass is washed out from the formed borehole by the water flow during the implementation of hydraulic punching, which avoids the sticking phenomenon that often occurred in the drilling construction in the soft coal seam and promotes the fracture expansion. So, hydraulic measures play great roles in improving the drainage effect of coalbed methane and changing the stress distribution of the coal mass around the borehole by helping to form a new gas flow channel. Many practices show that the hydraulic fractures are often unstable and difficult to maintain and thus lead to the stress concentration in local coal mass and even the occurrence of outburst. Compared with the disadvantages, hydraulic measures have been widely used as results of their significant improvement in the permeability of coal seams. In recent years, researchers are interested in the deformation and failure of coal in the process of hydraulic transformation, and some modern equipment including electromagnetic radiation signal, acoustic emission monitoring, and DC resistance experiment is used to monitor this process. Numerical simulation software is also widely used to simulate and predict the effect of hydraulic transformation measures because of its convenient and high efficiency.

With the development of computer technology, numerical simulation software is gradually used in the simulation and prediction of the engineering application process to quickly obtain the optimal construction parameters. The development of relevant theories is the basis of numerical simulation software. The multiphysical field coupling theory of gas drainage originated from the soil consolidation theory at the earliest. Later, a large number of scholars extended and developed the theory, thus a gradually formed relevant theoretical system of gas drainage.

The problem of fluid—solid deformation coupling was first studied by Terzaghi. He built a one-dimensional soil solid structure model based on the effective stress formula after proposing the effective stress formula. Furthermore, he also extended the one-dimensional structure model and proposed a three-dimensional solid structure model. Then, Biot explored the coupling law between the pore pressure and three-dimensional deformation materials based on Terzaghi’s theory and proposed a more complete theory on three-dimensional consolidation, which laid the theoretical foundation for fluid—solid coupling.

Gas drainage is a coupling process of multiphysical fields. Different physical fields interact to jointly affect the dynamic response of gas migration channels, change the deformation of the coal skeleton and matrix, and thus affect the effect of gas drainage. Many scholars have done a lot of research on the multiphysical field problems that affect the process of gas drainage, and the fluid solid coupling problem in the process of extraction has been gradually improved with the development of relevant theory. To determine the reasonable distance of gas predrainage drillings in coal seams, Lin et al. constructed a solid—gas coupling model that takes the gas adsorption effect into account and conducted the numerical simulation of predrainage gas in drillings along coal seam in view of different adsorption constants. Xue et al. implemented a fully thermo-hydro-mechanical (THM) coupled model that represents the nonlinear responses of gas extraction to demonstrate the reliability of this model through history data matching. Connell has carried out the simulation test of coal permeability under true triaxial conditions and established the permeability model considering the coupling effect of the stress field and gas pressure field. Fan et al. present a coupled compositional flow model by integrating the methane—air mixture flow in the fracture, methane flow within the matrix, mass transfer between fractures and matrixes, and permeability evolution induced by gas depletion, which is successfully validated against two sets of in situ gas drainage data. Xu et al. developed the gas seepage unit model around the borehole, and the theoretical mathematical expression to calculate the effective extraction radius is derived. Then, the numerical simulation of gas extraction is carried out through a computational fluid dynamics program, and the effective extraction radius is obtained numerically.

Unlike coal seams with a single degree of damage, soft—hard composite coal seams contain both coal seams with a higher degree of damage and a lower degree of damage. In view of this situation, few relevant studies and conventional hydraulic transformation measures have still been taken. Due to the differences in physical and mechanical characteristics of soft—hard composite coal seams, the damage degree of hard coal by hydraulic measures is lower than that of soft coal, causing uneven and unthorough reservoir pressure relief.

In this paper, layered hydraulic flushing technology is proposed by combining with the advantages of protective layer mining and hydraulic flushing in view of the complex storage conditions of soft—hard composite coal seams. Then, combined with numerical simulation software, this paper compares the effect of layered hydraulic flushing technology and conventional hydraulic flushing on pressure relief and permeability enhancement in soft—hard composite coal seams, and finally, the result is verified in field application. This paper puts forward a new technical idea for the current situation of pressure relief and permeability enhancement in complex coal seams, which improves the relevant drainage methods effectively, plays a great role in promoting the drainage of...
coalbed methane in coal mines, and can not only improve the safety of mine production but also reduce the pollution to the environment by decreasing the emission of coalbed methane.

2. GEOLOGICAL SETTING

2.1. Structure Setting. The Xin'an coal mine is located in Yima coalfields, West Henan province, China, which belongs to the fold fault bundle of Mianchi-Queshan depression in Huaxiong platform margin depression of the north China platform. No. II_1 coal seam is the main coal seam in Xin'an coal mine, which is adopted in inclined shaft double level up-warding and down-warding development, with the portal elevation of +305 m. The whole coalfield is divided into east and west wings, and there are 11, 13, and 15 districts in the east wing and 14 and 16 districts in the west wing. The mine is a gentle simple monoclinic structure with few large- and medium-sized fault structures. Also, the relatively large-scale faults mainly include F58, F2, and F29, and they are all mine field boundary faults (Figure 1).

2.2. Coal Seams. Similar to North China, the coal-bearing strata of Xin'an mine belong to the Carboniferous and Permian systems, including Taiyuan Formation, Shanxi Formation, Lower Shihezi Formation, and Upper Shihezi Formation. Among them, Shanxi Formation is the main coal-bearing stratum of this coal mine.

The total thickness of coal-bearing strata is about 576 m, including six groups of coal seams, and the total thickness of the coal seams is 7.30 m. Most part of the No. II_1 coal seam in the whole coalfield is minable, and other coal seams are not minable or occasionally minable. The minable coal seam is 0–18.88 m thick, with an average thickness of 4.22 m.

The coal petrography of No. II_1 coal seam is characterized by black, powdery, mainly clarain, with durain taking the second place, the macrocoal petrography is semibright coal, and pyrite nodules are occasionally seen. In the upper and lower parts of the coal seam, there is cataclastic coal with a low degree of failure with an average thickness of about 1 m, and the middle is basically mylonite coal with a high degree of failure, which is generally represented as the soft–hard composite coal seam.

2.3. Mine Gas. According to the actual situation revealed by exploration and mine production, the mine gas mainly shows the following characteristics: The outcrop of No. II_1 coal seam in the shallow part is the escape boundary. Also, the closed faults (F2, F29, and F58) located in the northeast and southwest ends of the coal seam block the gas. The gas content in the deep part gradually rises with the increase in the burial depth of the coal seam, and the gas content isoline is consistent with the contour of the coal seam floor or intersects at a small angle. The gas content of the line at the elevation of +150 m is about 4 m^3/t, and that of the line at the depth of −100 m in the mine field reaches more than 10 m^3/t. In the gas zone, between 14 and 19 exploration lines (local sections of the east first and east third districts) of the +50−100 m elevation, there is an oval gas weathering zone with the axis in the line 1508−1606−1707−1809−1907. The gas content in the zone is significantly lower than the normal value, and the minimum gas content is only 3.69 m^3/t. The gas content in the coalfield has an obvious high value area and low value area, and the low value area in the upper part is also the distribution area of the gas weathering zone. The maximum gas content of the high value area, which locates between −25 and 125 m in elevation as well in the range of 11–16 exploration lines, reaches 12.42 m^3/t. The gas content isoline is shown in Figure 1b.

The gas outburst in the mine first occurred in the haulage dip of district 14. After that, the gas outburst occurred many...
times. The overall feature is that the outburst mainly occurred in district 14 in the west, followed by district 13 in the east, and it is expected that districts 14, 13, and 16 in the first level of the mine have outburst risks.

3. LAYERED HYDRAULIC PUNCHING MEASURES AND NUMERICAL SIMULATION ANALYSIS

3.1. Layered Hydraulic Flushing Principle. Layered hydraulic flushing technology mainly combines the mining of the protective layer and hydraulic flushing technology and then adopts a high-pressure water jet to rush out the soft coal seam of the soft-hard composite coal seam for pressure relief. As a result, a horizontal cavity connecting the whole weak stratification will be formed, which will promote the expansion and deformation of the top and bottom coal mass, thereby increasing the permeability of the whole coal seam and improving the drainage effect.

The pressure relief method of this technology is similar to the mining of the protective layer, which aims to appropriately reduce the amount of coal output by the drainage boreholes for alleviating the difficulties of slag discharge in the boreholes. This is to realize the great and uniform improvement of the coal seam permeability under the condition of an appropriate amount of coal output and achieve a better drainage effect at the same time (Figure 2).

3.2. Comparative Analysis of Numerical Simulation. As a kind of porous medium, coal mass has complex macrofractures, microfractures, and porosity. The effective stress on the porous medium will change because the initial stress balance state of the reservoir is broken by the disturbance of a high-pressure water jet, which will cause the porosity and permeability of coal mass to also change. The gas migration state in coal seams is broken by continuous drainage. Meanwhile, the adsorption and desorption of gas in coal reservoirs will lead to the expansion and deformation of coal mass and the shrinkage of the matrix.

Therefore, to study the process of gas migration and production after flushing, it is necessary to comprehensively consider the coupling effect of the fracture field, deformation field, and gas seepage field. To highlight the advantages of layered hydraulic flushing technology, it is compared with conventional hydraulic flushing, and then pressure relief and drainage effects of the two flushing methods are simulated by numerical simulation software.

The method mainly includes the following: first, the fluid—solid coupling model of gas drainage considering the fracture field, deformation field, and seepage field is constructed. Second, the initial stratum model and borehole physical model of conventional hydraulic flushing and layered hydraulic flushing are constructed, and the relevant parameters and boundary conditions of the model are set according to the actual geological conditions. Finally, the simulation results of the two flushing methods are compared and analyzed.

3.3. Mathematical Model. 3.3.1. Basic Assumptions. The migration and production of gas in coal reservoirs involve many subjects, including seepage mechanics, solid mechanics, material mechanics, and rock mechanics. It is necessary to introduce assumptions as the basis for establishing fluid—solid coupling partial differential equations (PDESs), as follows:

1. Gas-bearing coal can be regarded as an isotropic elastic medium.
2. The coal seam is considered homogeneous.
3. The coal seam temperature is constant.
4. The gas in the coal seam is regarded as an ideal gas, and the gas desorption obeys the Langmuir equation.
5. The seepage characteristic of coalbed methane in coal meets the Klinkenberg effect.
6. The deformation of coal is small.
7. The overall deformation of coal consists of pore and fracture deformation.
8. Single-phase saturated gas fluid exists in the coal seam, and only free and adsorbed states are available.
9. The model is isolated from the outside, and there is no exchange of energy and matter in any form.

3.3.2. Mathematical Model of Porosity and Permeability. Gas-bearing coal is a complex deformable pore—fracture dual-medium, which has a strong adsorption capacity for gas and produces a certain adsorption expansion stress that will change the stress distribution of coal. Therefore, the relationship between the effective stress of the coal mass and its adsorption—expansion stress should be considered simultaneously when studying the problem of fluid—solid coupling of coal mass and gas. The porosity change of coal can be expressed as follows according to the relevant definition:

\[ \varphi = \frac{V_p}{V_b} = \frac{V_p + \Delta V_p}{V_b + \Delta V_b} = 1 - \frac{1 - \varphi_0}{1 + \epsilon} \left( 1 + \frac{\Delta V}{V_0} \right) \]  

(1)

where \( \varphi \) is the porosity, \( \varphi_0 \) is the initial porosity, \( V_p \) is the pore volume, \( V_p0 \) is the initial pore volume, \( V_b \) is the total apparent volume, \( V_b0 \) is the initial total apparent volume, \( \Delta V_p \) is the variation in the pore volume, \( \Delta V_b \) is the total apparent volume change in coal, \( V_b0 \) is the volume of the coal mass framework, \( \Delta V_b \) is the volume variation of the coal mass framework, and \( \epsilon \) is the volumetric strain.

We can refer to the Kozeny—Carman equation to establish the relationship between permeability and porosity:

\[ k = \frac{\varphi \left( \frac{V_p}{A_S} \right)^2}{k_2} \]  

(2)

where \( k \) is the permeability (mD), \( k_2 \) is a dimensionless constant, and \( A_S \) is the total surface area of the pore.
(cm$^3$) that is almost unchanged in the process of stress and strain. The ratio of permeability to initial permeability can be written as:

$$\frac{k}{k_0} = \frac{1}{1 + e} \left( \frac{V_{p0} + \Delta V_p}{V_{p0}} \right)^3 = \frac{1}{1 + e} \left( \frac{1 + \Delta V_p}{1 + \phi_0} \right)^3$$

where $k_0$ is the initial permeability (mD), and $\phi$ is the increasing coefficient of the pore surface area (%), which is approximately zero.

According to ref 65:

$$\frac{\Delta V_p}{V_{p0}} - \frac{\Delta P(1 - \phi_0)}{\phi_0K_s} = \frac{2aPRT \ln(1 + bP)}{3\phi_0V_nK_s} - \frac{\Delta P(1 - \phi_0)}{\phi_0K_s}$$

(4)

Thus, eq 3 can be simplified as follows:

$$k = \frac{k_0}{1 + e} \left[ 1 + e + \frac{\Delta P(1 - \phi_0)}{\phi_0K_s} - \frac{2aPRT \ln(1 + bP)}{3\phi_0V_nK_s} \right]^3$$

(5)

where $T$ is the thermodynamic temperature of the coal seam (K), $a$ is the limit adsorption capacity per unit mass of combustibles under a reference pressure (m$^3$/Mg), $b$ is the adsorption constant (MPa$^{-1}$), $R$ is the universal gas constant ($R = 8.3143$ J/(mol·K)), $\rho$ is the coal density (kg/m$^3$), $V_n$ is the molar volume of gas (22.4 × 10$^{-3}$ m$^3$/mol), and $K_s$ is the volume modulus of the coal skeleton (Pa).

3.3.3. Deformation Field Equation of Gas-Bearing Coal.

In accordance with the effective stress law of Terzaghi and in consideration of the expansion stress absorbed by coal, the effective stress equation of gas-bearing coal can be expressed as follows:

$$\sigma'_j = \sigma_j - aP\phi_j - \sigma_j$$

(6)

where $\sigma'_j$ is the effective stress of gas-bearing coal (MPa), $\sigma_j$ is the whole stress (MPa), and $a$ is the Biot coefficient. $\sigma_j$ is the expansion stress (Pa) that can be expressed as follows:

$$\sigma_j = E\epsilon_j = \frac{2aPRT(1 - 2v)\ln(1 + bP)}{3V_n}$$

(7)

where $v$ is the Poisson ratio, and $E$ is the elastic modulus of coal (Pa).

The stress balance differential equation of gas-bearing coal and rock is expressed in tensor form as follows:

$$\sigma_{ij} + F_i = 0 \quad (i, j = 1, 2, 3)$$

(8)

where $F_i$ is the bulk stress (N/m$^3$).

The effective stress formula (eq 6) is brought into eq 8 to obtain the stress balance differential equation expressed by the effective stress:

$$\sigma'_{ij} + (aP\phi_j) + (\sigma_j\phi_j) + F_i = 0$$

(9)

In the spatial distribution of gas-containing coal, let $u(x, y, z)$, $v(x, y, z)$, and $w(x, y, z)$ be the displacement components in directions $x$, $y$, and $z$, respectively, and continuous single-valued functions of coordinates. Then, the strain and displacement components satisfy the following geometric equations, which can be expressed as tensor symbols:

$$\epsilon_{ij} = \frac{1}{2}(u_{ij} + u_{ji}) \quad (i, j = 1, 2, 3)$$

(10)

The constitutive relationship in this study is based on the strains caused by the adsorption expansion of gas-containing coal, compression of the coal particle mass, and crustal stress. The total strain of gas-bearing coal is as follows:

$$\epsilon = \epsilon_X + \epsilon_Y + \epsilon_D$$

(11)

where the linear strain caused by gas adsorption by coal particles is $\epsilon_{X0}$, the linear compression strain of coal particles caused by the change in pore gas pressure is $\epsilon_{Y0}$, the strain due to crustal stress is $\epsilon_D$, and:

$$\epsilon_X = \frac{2aPRT \ln(1 + bP)}{9V_nK_s}$$

$$\epsilon_Y = \frac{\Delta P}{3K_s}$$

$$\epsilon_D = \frac{1}{2G} \left( \sigma' - \frac{\nu}{1 - \nu} \Theta' \right)$$

$$\Theta' = \sigma'_x + \sigma'_y + \sigma'_z = eK_s$$

(12)

where $G$ is the shear modulus (MPa), and $\Theta'$ is the effective volume stress. Introducing the Lame constant $\lambda$:

$$\lambda = \frac{E\nu}{(1 + \nu)(1 - 2\nu)} = \frac{2G\nu}{1 - 2\nu}$$

(13)

Thus, $\sigma'$ can be obtained by arranging eqs 11–13:

$$\sigma' = 2Ge + \lambda\epsilon + \frac{2G\Delta P}{3K_s} - \frac{4GapRT}{9V_nK_s} \ln(1 + bP)$$

(14)

Assuming that the coal is a linear elastic medium, the constitutive equation of gas-containing coal deformation conforms to Hooke’s law, as follows:

$$\sigma'_j = \lambda\phi_j + 2Gej$$

(15)

According to the stress–strain relationship of coal in eq 15 and in combination with the above formula, the effective stress constitutive equation of gas-containing coal expressed in tensor form is derived as follows:

$$\sigma'_{ij} = \lambda\phi_{ij} + 2Ge_{ij} + \frac{2G\Delta P}{3K_s} - \frac{4GapRT}{9V_nK_s} \ln(1 + bP)$$

(16)

Substituting eq 16 into eq 9 yields the following:

$$G \sum_{j=1}^{3} \frac{\partial^2 u_i}{\partial x_j^2} + \frac{G}{1 - 2\nu} \sum_{j=1}^{3} \frac{\partial^2 u_i}{\partial x_j \partial x_j} + \left[ \alpha + \frac{2G}{3K_s} + \left( \frac{1 - 2\nu}{V_n} - \frac{2G}{3V_nK_s} \right) \frac{2abPRT}{3(1 + bP)} \right] \frac{\partial P}{\partial x_i} + F_i = 0$$

(17)
3.3.4. Fluid—Solid Coupling Gas Seepage Equation of Gas-Bearing Coal. The state equation of coal seam gas under the ideal gas state is expressed as follows:

$$\rho_g = \frac{M_g P}{RTZ} = \frac{\rho_n P}{P_n Z}$$  \hspace{1cm} (18)

where $\rho_g$ is the gas density when the gas pressure is at $P$ (kg/m$^3$), $M_g$ is the molar mass of gas (kg/mol), $Z$ is the gas compression factor, which is approximately 1 when the temperature difference is not large, $\rho_n$ is the coal seam gas density in the standard state (kg/m$^3$), and $P_n$ is the gas pressure under standard conditions ($P_n = 0.10325$ MPa). The occurrence state of coal seam gas is mainly the adsorbed state and free state. According to the modified Langmuir adsorption equilibrium equation, the equation for the total coal seam gas content is:

$$Q = \frac{abP}{1 + bP} \left( \rho_1 - A - M \right) + \varphi \frac{P}{P_n} \rho_n$$  \hspace{1cm} (19)

where $Q$ is the gas content of coal per unit volume (kg/m$^3$), $A$ is the ash content of coal (%), and $M$ is the moisture content of coal (%). When the Klinkenberg effect is considered, the equation of gas flow in the coal seam can be expressed by the following:

$$q = \frac{k}{\mu} \left( 1 + \frac{m}{P} \right) \nabla P$$  \hspace{1cm} (20)

where $q$ is the velocity vector of gas flow (m/s), $\mu$ is the gas dynamic viscosity ($1.08 \times 10^{-5}$ Pa·s), and $\nabla P$ is the gas pressure gradient (Pa/m).

According to the hypothesis, if the model is isolated from the outside and no exchange of substance and energy in any form occurs, the gas flow in the coal seam will conform to the law of conservation of mass, expressed in the form of a differential equation:

$$\frac{\partial Q}{\partial t} + \nabla \cdot (\rho_g q) = 0$$  \hspace{1cm} (21)

Simultaneously arranging eqs 18–21:

$$\frac{M_g}{RT} \left[ \frac{\varphi}{(1 + bP)^2} + \frac{(1 - \varphi_n)P}{(1 + c)K} \right] \frac{\partial P}{\partial t} - \frac{2abP}{3V_e k_e (1 + bP)} \frac{\partial P}{\partial t} = - \frac{M_g}{RT} \frac{k}{\mu} \left( 1 + \frac{m}{P} \right) \nabla P$$

$$= - \frac{M_g}{RT} \frac{k}{\mu} \left( 1 + \frac{m}{P} \right) \nabla P$$

In summary, eqs 5, 17, and 22 constitute a fluid—solid coupling model of gas-containing coal.

3.4. Numerical Simulation Physical Model. 3.4.1. Boreholes Morphology of Two Flushing Methods. There are few related research studies on the morphological characteristics of the boreholes after layered hydraulic flushing. The test pieces are flushed through a water jet in the laboratory. Considering that the strength of cement after solidification is much greater than that of these specimens, the cement was poured into the boreholes so that the borehole shape can be obtained relatively completely when the specimens were cut. It is a cylinder with a circular end as shown in Figure 3.

For the research of the conventional hydraulic flushing borehole morphology, based on the Bergmark–Roos equation, Li et al. introduced the force of water flow on the basis of gravity and friction and then proposed a revised Bergmark–Roos equation. At last, they obtained the conventional hydraulic flushing borehole shape with the help of drawing software, which is an approximate ellipsoid with the top slightly larger than the bottom as shown in Figure 3.

The shape of the layered hydraulic flushing borehole is simplified as a cylinder with a circular end, and the conventional hydraulic flushing borehole shape is simplified as an ellipsoid for facilitating the embedding of the model in the numerical calculation.

3.4.2. Related Parameter Setting. During simulation, the borehole length of layered hydraulic flushing in Figure 3 is preset as 5.2 m, and the diameter of the borehole after flushing is 0.8 m. As mentioned earlier, the borehole of layered hydraulic flushing is simplified as a cylinder with a circular end.
The volume of the borehole can be calculated to be about 2.88 m³ by the volume calculation formula of the cylinder and sphere. As mentioned above, the length of the whole coal section in the model is 4 m. As the conventional hydraulic flushing technology pursues the whole coal section flushing, the semi-major axis of the conventional flushing borehole in Figure 3 is 2 m. Under the condition that the borehole volume of layered hydraulic flushing and conventional hydraulic flushing is the same, the short semi-axis can be reversely deduced to be 0.58 m.

The size of the stratigraphic model shown in Figure 4 is 16 m × 16 m, and the thickness of coal seam is 4 m. A vertical pressure of 15 MPa is applied to the upper part of the model, and 13 MPa horizontal pressure is applied to both sides. Table 1 shows the relevant parameters of the fluid—solid coupling model of gas-bearing coal.

| parameter name          | symbol | unit       | numerical value |
|-------------------------|--------|------------|-----------------|
| coal density            | \(\rho\) | kg m⁻³     | 1420            |
| Poisson’s ratio of coal | \(\nu\) |            | 0.32            |
| elastic modulus of coal | \(E\)  | GPa        | 2.74            |
| initial porosity of coal| \(\varphi_i\) |            | 0.0485          |
| initial permeability of coal| \(k_0\) | m²·s⁻¹ | 4.59 × 10⁻¹⁷ |
| adsorption constant \(a\) |          | m⁻³·Mg⁻³ | 35              |
| adsorption constant \(b\) |          | MPa⁻¹ | 0.762           |
| gas dynamic viscosity coefficient | \(\mu\) | Pa·s | 1.08 × 10⁻⁵ |
| moisture                | \(M\)  | %          | 0.64            |
| ash                     | \(A\)  | %          | 13.81           |
| gas density in the standard state | \(\rho_g\) | kg m⁻³ | 0.716           |
| initial gas pressure    | \(P_0\) | MPa        | 0.9             |
| drainage negative pressure | \(P_d\) | Pa        | 13,000          |

4. RESULTS AND DISCUSSION

The pressure of the coal mass around the borehole is rapidly relieved after the completion of hydraulic flushing. The stress of the coal mass is redistributed because it changes suddenly, which results in the permeability of the coal mass improving. The effects of two flushing methods on the changes of gas content and pressure are obtained according to the results of numerical simulation, and they are compared and analyzed respectively.

4.1. Comparative Analysis of Stress and Gas Content

Figure 5 shows the stress contour around the borehole after the reconstruction of conventional hydraulic flushing and layered hydraulic flushing. There is local stress concentration at the top and bottom of the conventional hydraulic flushing borehole, and the stress on both sides of the borehole decreases with the distance from it; however, the stress on both sides is still in a pressure relief state because it is less than the initial pressure. The relief of stress caused by layered hydraulic flushing occurs in the upper and lower parts of the borehole, and the stress concentration occurs on both sides of the borehole.

Figure 6 shows the gas content change curve of the two flushing methods in the horizontal direction of the boreholes. With the increase in horizontal distance, the gas content in coal mass gradually returns to a stable initial value. The gas content changes significantly within 10 days whether conventional hydraulic flushing or layered hydraulic flushing is used, and after 10 days, the change of gas content is no longer obvious.

It can be seen from the comparison that the layered hydraulic flushing has a great impact on the gas content when the distance in the horizontal direction is within 1 m, and the gas content quickly drops below 23 m³. When the distance is greater than 1 m, the gas content drop is no longer obvious; for conventional hydraulic flushing technology, the gas content can be reduced to less than 23 m³ when the horizontal distance of the borehole is within 1.8 m.

In Figure 5, the red stress concentration area in the stress contour around the conventional hydraulic flushing borehole is distributed at the top and bottom of the borehole, and the blue pressure relief area is located at both sides. Meanwhile, the red stress concentration area in the stress contour around the layered hydraulic flushing borehole is distributed at both sides of the borehole, and the blue pressure relief area is located at the top and bottom. In the horizontal direction of Figure 6, the curve area of conventional hydraulic flushing is larger than that of layered hydraulic flushing under the same gas content, which means that the pressure relief range of conventional hydraulic flushing in the horizontal direction is larger. We can know that the disturbance of the conventional hydraulic flushing to the coal mass stress is mainly reflected in the horizontal direction, while that of the layered hydraulic flushing to the coal seam stress is mainly reflected in the vertical direction.

4.2. Comparative Analysis of the Gas Drainage Range

Figure 7 shows the contour of gas pressure evolution within 30 days of conventional hydraulic flushing. It can be seen that in the first 10 days of drainage, the stress state of coal mass is still not stable and the gas pressure state changes greatly. After 10 days of drainage, the gas pressure state is gradually stable and the change is no longer obvious. The black solid line on both sides of the borehole in the figure represents the isoline where the gas pressure is 0.74 MPa; within the solid line is the effective drainage range, which is regarded as an ellipsoid.

In the cloud contour of gas pressure, the abscissa of isoline in the horizontal direction can be read when the gas pressure is 0.74 MPa. The maximum distance between the isoline and the borehole center can be obtained through the abscissa, and then the effective drainage range at different times can be obtained according to the volume formula of the ellipsoid. According to the calculation results, when the drainage time is 1 day, the...
effective drainage range is 8.04 m$^3$, which is 18.09 m$^3$ in 10 days and 19.09 m$^3$ in 30 days.

Figure 8 shows the evolution contour of gas pressure in 30 days of layered hydraulic flushing. It can be seen that the change of gas pressure state is close to that of conventional hydraulic flushing. In the first 10 days of drainage, the gas pressure state changes greatly. After 10 days of drainage, the gas pressure state gradually becomes stable.

Similarly, the abscissa and ordinate of the isoline in the horizontal and vertical directions can be read out when the gas pressure is 0.74 MPa. The maximum distance from the isoline to the center of the borehole can be obtained through the coordinates, and the effective drainage range at different times can be obtained according to the volume formula of the cylinder. According to the calculation results, when the drainage time is 1 day, the effective drainage range is 13.28 m$^3$, which is 26.89 m$^3$ in 10 days and 27.42 m$^3$ in 30 days.

4.3. Comparison and Analysis. Compared with Figures 7 and 8, it can be seen that with the increase in drainage time, the effective gas drainage range of layered hydraulic flushing is larger than that of conventional hydraulic flushing (Table 2).
Table 2. Effective Drainage Range at Different Times

| Time (day) | Effective Drainage Range (m³) | Time (day) | Effective Drainage Range (m³) |
|-----------|-------------------------------|-----------|-------------------------------|
| 1         | 8.04                          | 1         | 13.28                         |
| 10        | 18.09                         | 10        | 26.89                         |
| 30        | 19.09                         | 30        | 27.42                         |

The gas pressure in coal mass remained basically stable whether it is conventional hydraulic flushing or layered hydraulic flushing after 30 days of drainage. Finally, it can be considered that the effective gas drainage range of conventional hydraulic flushing is 19.09 m³, that of layered hydraulic flushing is 27.42 m³, and the difference between them is 8.33 m³. Therefore, it can be considered that regardless of the pressure-releasing effect or the drainage effect, the advantages of layered hydraulic flushing are greater.

**4.4. Case Study.**

**4.4.1. Basic Profile of the Working Face.**

The average thickness of the coal seam in the 14250 working face is about 4.1 m, and about 1 m hard coal is developed in the upper and lower parts of the coal seam, with mylonitic coal in the middle. The roof is mudstone with an average thickness about 4 m, the bottom is siltstone with a thickness about 10 m, and the old bottom is siliceous mudstone with hard texture. The rock roadway is basically excavated along the old bottom, and gas drainage is carried out by crossing-seam boreholes. Gas geological characteristics consult the 14230 working face adjacent to the working face. The coal seam outside the upper roadway of the 14230 working face is about 4.3 m thick. The original gas content of the coal seam in this working face is 8.0–10.98 m³/t.

**4.4.2. Borehole Layout.**

To compare the effects of layered hydraulic flushing and conventional hydraulic flushing, five groups of test boreholes are set up in the starting cutting floor roadway. The specific test boreholes are in rows 7–11. It is expected that 13 boreholes will be arranged in each test group. Since 1# and 2# design boreholes are located in the pressure relief zone, drilling and flushing will not be carried out. At the same time, because the 1#, 2#, 3#, 4#, 12#, and 13# boreholes with a dip angle of less than 40° are unstable after layered hydraulic punching, only 5–11# boreholes in each row are tested, which are marked in Figure 9 (the blue boreholes represent the test boreholes). The borehole diameter is 113 mm with the depth extending to at least 2 m above the coal seam roof. Meanwhile, the projection spacing of the boreholes is 4.2 m, and the spacing of the two adjacent rows of boreholes is 6 m.

**4.4.3. Analysis of Drainage Data.**

The drainage data of rows 8, 9, and 10 of test boreholes, which are relatively complete, are compared with those of rows 4, 5, and 6 of conventional boreholes. The monitored gas concentration curves are shown in Figure 10. It shows the variation curve of drainage concentration in test boreholes. Since the drainage of the mining area of 14 was stopped from April 27 to May 24, there were no sampling data in rows 8 and 9 during this period. In this figure, it can be seen that there is no obvious regularity in the change trend of gas concentration in the three rows of boreholes, and the drainage concentration increases repeatedly with not a few data points greater than 40%. We can see that the concentration changes of the three rows of boreholes are discrete by analyzing the data of each row of boreholes separately. With the increase in drainage time, the variation trend of drainage concentration between boreholes is different.

Figure 11 shows the concentration change curve of conventional hydraulic borehole drainage. It is not difficult to find that compared with test boreholes, the change trend of the gas concentration is obvious. The three rows of boreholes as a whole show a downward trend, and the concentration variation trend of each borehole in each row is also relatively uniform.

In addition, it is obvious that the gas drainage concentration of conventional boreholes is generally low. The maximum concentration of all other boreholes is less than 40%, except that the 5-row 6# borehole can reach 70% at the beginning. The advantages of the drainage effect of the test boreholes with layered hydraulic flushing can be clearly compared.

**4.5. Discussion.**

Figure 12 shows the variation curve of the average gas drainage concentration in test boreholes and conventional boreholes. Generally, it can be seen that the average gas concentration change curve of the test boreholes has no obvious increase or decrease trend with the increase in drainage time instead of irregular ups and downs. Meanwhile, the average gas concentration curve of conventional boreholes shows a downward trend with the increase in drainage time. In terms of specific drainage data, the average gas drainage concentration of each row of test boreholes is more than 40% in the initial stage of drainage and has shown different increases with continuous drainage time.

The highest average gas concentration in the eighth row of test boreholes is about 90%, which occurs 12 days after drainage. The highest average gas concentration in the ninth row of test boreholes is about 85%, which occurs 30 days after drainage. The highest average gas drainage concentration in the 10th row of test boreholes is about 80%, which occurs 3 days after drainage. The highest average gas drainage concentration in test boreholes is 40% of the fifth row, and those of the other three rows are about 20%, which is relatively low compared with those in the test boreholes. Moreover, it can be seen that the average gas drainage concentration is greater than 20% in the vast majority of days of test boreholes, while conventional flushing is only higher than 20% in the fourth row of boreholes, and it only lasts for 2 days. Therefore, it can also be seen that there is a great difference in the drainage effect between layered hydraulic flushing and conventional hydraulic flushing.

In Figures 10 and 12, it can be seen that the trend of the drainage concentration curve of the test boreholes shows irregular changes of rising and falling repeatedly, which may be
due to the particularity of the flushing boreholes formed by the layered hydraulic flushing technology. This is because the influence of layered hydraulic flushing on the stress state of coal is mainly in the vertical direction, which leads to the fractures continuing to form vertically with the change of time.

It can be seen from the analysis results of physical similarity experiment in Figure 13 that during the process of borehole formation, the continuous deformation, even the collapse and compaction of the upper coal mass, results in the repeated dynamic change process of coal permeability characteristics. The permeability of the coal mass is improved due to the pressure relief and extensive development of fractures in the initial period after the formation of the borehole, and the gas drainage effect initially appears. The borehole is relatively stable in the short term, and then the gas drainage effect gradually decreases as the gas content around the borehole decreases. However, extraction is continuous, and the coal mass around the borehole may be disturbed again for desorption, the discharge of gas, and the softening effect of water so that the coal mass is constantly destroyed. Therefore, it may cause the drainage effect to be suddenly improved for a short time because the fractures develop again (Figure 13a–c) and the coal mass even collapses locally (Figure 13b,c). That is why there will be repeated changes in the gas concentration drainage curve in Figures 10 and 12.

5. CONCLUSIONS

(1) The disturbance of the conventional hydraulic flushing to the coal mass stress is mainly reflected in the horizontal direction, while that of the layered hydraulic flushing to the coal seam stress is mainly reflected in the vertical direction.

(2) According to the numerical simulation results, after 30 days of drainage, the effective gas drainage range of conventional hydraulic flushing is 19.09 m³, that of layered hydraulic flushing is 27.42 m³, and the difference between them is 8.33 m³.
There is no obvious regularity in the change trend of gas concentration in the test boreholes, and the drainage concentration increases repeatedly, while the conventional boreholes as a whole show a downward trend.

The drainage concentration of test boreholes increases repeatedly with not a few data points greater than 40%, while the maximum concentration of all other boreholes is less than 40%, except that the S-row 6# borehole can reach 70% at the beginning. At the same time, the average gas drainage concentration is greater than 20% in the vast majority of days of test boreholes, while the conventional flushing is only higher than 20% in the fourth row of boreholes, and it only lasts for 2 days. The advantage of layered hydraulic punching technology is obvious.

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Notes
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