Research Article

Investigation of Large-Diameter Borehole for Enhancing Permeability and Gas Extraction in Soft Coal Seam

Yongwen Wang,¹ Wanjun Yan,² Zhongjiu Ren,³ Zhiqiang Yan,¹ Ziwen Liu,³ and Heng Zhang³

¹Shanxi Fenxi Mining (Group) Co., Ltd., Jinzhong, Shanxi Province 141122, China

²Zhongxing Coal Industry, Shanxi Fenxi Mining (Group) Co., Ltd., Lüliang, Shanxi Province 141122, China

³Shenyang Research Institute, China Coal Technology and Engineering Group, Shenyang, Liaoning Province 110016, China

Correspondence should be addressed to Heng Zhang; zhangheng99100@163.com

Received 21 October 2020; Revised 25 November 2020; Accepted 12 December 2020; Published 30 December 2020

Academic Editor: Yi-Dong Cai

Copyright © 2020 Yongwen Wang et al. This is an open access article distributed under the Creative Commons Attribution License, which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

The efficiency of gas extraction from the soft coal seam with ultralow permeability is low. Gas extraction with large-diameter borehole is proposed to deplete gas content for preventing gas outburst disaster in this study. The fractures around the large borehole will enhance the permeability in the damage area to promote gas extraction. We established a damage-stress-seepage coupling model for large-diameter borehole gas extraction in soft coal seam. This mathematical model contains governing equations of gases sorption and transport, coal deformation, and damage, reflecting the coupling responses between gas and coal seam. The model is solved by the finite element method to simulate the gas drainage large-diameter borehole through roadway. Distributions of elastic modulus, damage area, and maximum principal stress in soft coal seam with different borehole diameters including 94 mm, 133 mm, 200 mm, and 300 mm are analyzed. The gas pressure, gas content, and effective extraction area in soft coal seam are discussed. Results show that the shear failure zone appears around the large-diameter borehole, and its permeability rises sharply. This opens up the gas transport channel and is conducive to the rapid extraction. It is confirmed that gas extraction using large-diameter borehole (300 mm) can greatly improve the efficiency of the gas preextraction in soft coal seam by increasing gas extraction rate. These provide a foundation for guiding the operation of gas extraction with large borehole from the soft coal seam in the field.

1. Introduction

Soft gassy coal seams with ultralow permeability are widely distributed in China, which may likely trigger coal and gas outburst [1–4]. This disaster usually occurs accompanying with large amount of crushed coal and gas, as well as violent shock and vibration [5]. Gas drainage can reduce the gas content and gas pressure within coal seams, which is an effective way to eliminate outburst disaster [6–8]. Many measures were applied to increase the preextraction efficiency in the soft coal seam, including hydraulic fracturing, hydraulic punching, and presplitting blasting, methane driven by gas injection [9–14]. However the effect is limited. The presplitting blasting method has high risks during the implementation process, which is confronted to many governing policies and laws of China [15, 16]. Gas injection will increase

the content of injected gas (CO₂ or N₂), which may lead to new hazards after eliminating gas (methane) outburst risk [17–20]. This method has little utilization by now [21, 22]. Indeed, the hydraulic fracturing has been widely used to increase the coal permeability because of its superior cutting capacity and low cost [23, 24]. However, the effect of hydraulic method is unsatisfactory in the soft coal seam. The hydraulic fractures trend to be closed after a while of the treatment in soft coal seams [25, 26]. Increasing the diameter of drilling borehole will increase the amount of fractures around the borehole and enhance the permeability of the coal seam [27, 28]. Hence, boreholes with large diameter are employed to effectively promote gas extraction in this study.

Scholars have investigated gas extraction by large-diameter boreholes in various situations. Zhao et al. studied the large-diameter borehole drainage technology in roof of

high gassy coal seams [29]. Dong et al. developed the drill pipe for large-diameter directional long hole in coal mine [30]. Hua et al. proposed the super large-diameter borehole to control gas content in the upper corner of coal mining working face [31]. Yuan et al. established the theory of gas drainage in goaf by large-diameter surface drilling boreholes [32]. Meanwhile, Gao and Yang devoted a super large-diameter borehole gob gas extraction technology to solve the problem of extraction deficiency caused by the unreasonable high-level drainage roadway layout [33]. For gas preextraction in coal seam, the gas drainage test of large-diameter horizontal long borehole in outburst coal seam was carried out, and the results showed that the gas drainage effect was significantly improved.

Although the large-diameter boreholes are successfully applied in the gas extraction filed in coal mine, the effect of borehole diameter on the efficiency of gas extraction in soft coal seam is not clear. Borehole drilling in coal seam will induce damage around the borehole and thus increase the fractures and the permeability in coal seam. The processes of drilling induced damage and gas extraction with enhanced permeability are much complex [34, 35]. The gas transport is greatly affected by the coupling relations between gas flow and coal geomechanics [2, 17]. This involves the processes of coal damage or deformation, gas desorption from coal matrix, gas diffusion within matrix pores, and gas flows from fractures to boreholes [36]. As the coupling terms, the permeability and porosity are largely influenced gas transport within coal seam [37]. Additionally, the effective stress will be altered when the operation of gas drainage continues, which will in turn cause coal deformation [38]. In following sections, a damage-stress-seepage coupling model will be established. The mathematical model will be applied to simulate the gas extraction in soft coal seam using large-diameter borehole. The mechanical characteristics, damage futures, and gas properties during gas extraction with different borehole diameters are analyzed and discussed to identify the controlling of large borehole diameter on permeability enhancement and gas extraction in soft coal seam.

2. Damage-Stress-Seepage Coupling Model for Gas Extraction in Soft Coal Seam

2.1. Basic Assumptions. According to the occurrence of coal seam gas, the following assumptions are put forward [14, 17, 18, 25, 34, 39–42]:

- (I) Coal mass is a kind of elastic medium with single permeability and dual pore-fracture structure, and its elastic modulus obeys the Weibull distribution
- (II) Groundwater only exists and migrates in fractures, and coal seam gas exists and migrates in pores and fissures in adsorbed and free state at the same time. Fractures are saturated by water and coal seam gas, and gas adsorption/desorption process is completed in an instant
- (III) The migration of coal seam gas is closely related to the pore structure of coal reservoir and is consid-

ered three steps in series (Figure 1): firstly, coal seam gas is desorbed from the pore wall of coal matrix, which meets the Langmuir adsorption law; secondly, under the effect of concentration gradient, coal seam gas diffuses from the pores of coal matrix into the fractures, which meets the Fick diffusion law; thirdly, the coal seam gas seeps into the gas well from the fracture, which meets the Darcy's law of seepage

- (IV) Coal seam gas is an ideal gas, which conforms to the state equation of ideal gas
- (V) The tensile stress is considered positive, while pore pressure negative.

2.2. Controlling Mathematic Equations. Coal seam is a kind of solid combustible mineral with pore-fracture structure. Its pore-fracture space is filled with a large amount of adsorbed or free coal seam gas and groundwater. Coal seam gas in coal matrix is composed of adsorbed and free gas. The quality of coal seam gas in unit volume of coal matrix can be defined as follows [10]:

$$m_m = \phi_m \rho_g + V_{sg} \rho_{gs}, \quad (1)$$

where ϕ_m is porosity in coal matrix; ρ_g is the density of coal seam gas, kg/m³; V_{sg} is gas content of adsorbed coal seam gas, m³/kg; ρ_s is the density of coal, kg/m³; and ρ_{gs} is the density of coal seam gas in standard state, kg/m³.

According to the ideal gas state equation, the density of coal seam gas can be defined as follows [3]:

$$\rho_g = \frac{M_g}{RT} p, \quad (2)$$

where M_g is the gas molar mass, kg/mol; R is the gas molar constant, J/(mol K); p is the gas pressure, MPa; and T is the coal seam temperature, K.

The adsorbed volume of coal seam gas in coal matrix at different temperatures can be expressed by the modified Langmuir equation (10):

$$V_{sg} = \frac{V_L p_m}{P_L + p_m}, \quad (3)$$

where V_L is Langmuir volume constant, m³/kg; P_L is the Langmuir pressure constant, Pa; and p_m is gas pressure in matrix, MPa.

The coal seam gas is in the dynamic equilibrium state of adsorption and desorption at the beginning. The pore gas pressure in the matrix is equal to the fractured gas pressure. When the equilibrium state is broken due to pumping, the adsorbed gas desorbs and migrates into the fracture system dominated by diffusion under the action of concentration gradient. The mass conservation equation of coal seam gas in coal matrix is as follows [3]:

FIGURE 1: Gas migration process during extraction from soft coal seam, modified from literature [43].

$$\frac{\partial m_m}{\partial t} = -\frac{M_g}{\tau RT} (p_m - p_{fg}), \quad (4)$$

where t is the time, s; p_{fg} is the pressure of coal seam gas in the fracture, MPa; and τ is the desorption time of coal seam gas, reflecting the emission capacity of coal matrix, which is equal to the time taken for the matrix to desorb 63.2% of coal seam gas.

By introducing equations (1) and (2) into equation (4), the transport equation of coal seam gas in coal matrix can be obtained [13]:

$$\frac{\partial}{\partial t} \left(\frac{V_L p_m}{P_L + p_m} \rho_s \frac{M_g}{RT_s} p_s + \varphi_m \frac{M_g}{RT} p_m \right) = -\frac{M_g}{\tau RT} (p_m - p_{fg}). \quad (5)$$

The coal matrix provides the mass source for the fracture, and the gas phase mass conservation equation of the fracture system is as follows:

$$\frac{\partial (\varphi_f \rho_g)}{\partial t} + \nabla \cdot (\rho_g \vec{q}_g) = (1 - \varphi_f) \frac{M_g}{\tau RT} (p_m - p_{fg}), \quad (6)$$

where φ_f is fracture porosity and $\vec{q}_g$ is coal seam gas flow rate, m/s.

Considering the slippage effect and the generalized Darcy law of gas-water two-phase seepage, the gas velocity of coal seam in fracture is [17]

$$\vec{q}_g = -\frac{k}{\mu_g} \left(1 + \frac{b_1}{p_{fg}} \right) \nabla p_{fg}, \quad (7)$$

where k is the absolute permeability of fracture, m^2 ; μ_g is the dynamic viscosity of gas phase, Pa s; and b_1 is the slippage factor, Pa.

By introducing equation (7) into equation (6), the governing equation of coal seam gas seepage field is obtained:

$$\begin{aligned} \frac{\partial}{\partial t} \left(\varphi_f \frac{M_g}{RT} p_{fg} \right) + \nabla \cdot \left(-\frac{M_g (p_{fg} + b_1)}{RT} \frac{k}{\mu_g} \nabla p_{fg} \right) \\ = (1 - \varphi_f) \frac{M_g}{\tau RT} (p_m - p_{fg}). \end{aligned} \quad (8)$$

Coal is a dual porosity medium, and its mechanical properties are affected by pores and fractures. The total strain of coal body is the sum of the strain caused by stress, the strain caused by gas and water, and the strain caused by gas adsorption and desorption [20]:

$$\varepsilon_{ij} = \frac{1}{2G} \sigma_{ij} - \left(\frac{1}{6G} - \frac{1}{9K} \right) \sigma_{kk} \delta_{ij} + \frac{\alpha_m p_m + \alpha_f p_{fg}}{3K} \delta_{ij} + \frac{\varepsilon_a}{3} \delta_{ij}, \quad (9)$$

where δ_{ij} is the Kronecker symbol; D is equivalent coal elastic modulus, GPa; G is coal shear modulus, GPa; K is coal bulk modulus, GPa; $K_s = E_s/3(1 - 2\nu)$ is coal skeleton bulk modulus, GPa; E_s is coal skeleton elastic modulus, GPa; k_n is fracture stiffness, GPa; ν is Poisson's ratio; α_m and α_f are Biot effective stress coefficients corresponding to pores and fractures, respectively; and a is the width of matrix, m.

The strain of coal seam gas adsorbed by skeleton is directly proportional to the adsorption amount [18, 44]:

$$\varepsilon_a = \alpha_{sg} V_{sg}, \quad (10)$$

where α_{sg} is the adsorption strain coefficient, kg/m^3 , and V_{sg} is the gas adsorption capacity, m^3/kg .

According to elastic mechanics, the geometric relationship and static equilibrium relationship of coal reservoir are as follows:

$$\begin{cases} \varepsilon_{ij} = \frac{1}{2} (u_{i,j} + u_{j,i}) \\ \sigma_{ij,j} + F_i = 0. \end{cases} \quad (11)$$

where F_i is the volume force, MPa; u_i is the displacement in i direction, m; and $i = x, y, z$.

According to equations (9) and (11), the modified Navier equation considering pore pressure, temperature variation, and adsorption is obtained:

$$Gu_{i,jj} + \frac{G}{1-2\nu}u_{j,ji} - \alpha_m p_{m,i} - \alpha_f p_{f,i} - K\varepsilon_{a,i} + F_i = 0. \quad (12)$$

Based on the damage mechanics theory, the elastic modulus of coal decreases with the occurrence of damage [10]:

$$E = E_0(1 - D), \quad (13)$$

where E and E_0 are elastic modulus of coal after and before damage, GPa, and D is damage variable.

Coal and rock are heterogeneous materials. We assume that the mechanical parameters of REV obey the Weibull distribution. The function of probability density is defined as

$$f(u) = \frac{m}{u_0} (u/u_0)^{m-1} \exp[-(u/u_0)^m], \quad (14)$$

where u is the mechanical parameter, such as elastic modulus, u_0 is the average of mechanical parameter, and m is an index of heterogeneity. The larger the value of m , the better the uniformity of mechanical parameters will be. In the following simulations, all elements were assigned different elastic modulus depending on the heterogeneity of coal seam.

The maximum tensile stress criterion and Mohr-Coulomb criterion are used to judge whether the tensile and shear damage occurs after the coal body is stressed [18]:

$$F_1 = \sigma_1 - \sigma_t = 0, \quad (15)$$

$$F_2 = -\sigma_3 + \sigma_1 \frac{1 + \sin \theta}{1 - \sin \theta} - \sigma_c = 0, \quad (16)$$

where σ_1 is the maximum principal stress, MPa; σ_3 is the minimum principal stress, MPa; σ_t and σ_c are the uniaxial tensile strength and uniaxial compressive strength of coal, MPa; θ is the internal friction angle of coal; and F_1 and F_2 are the threshold functions of tensile and shear damage, respectively. In the process of damage calculation, firstly, the maximum tensile stress criterion is used to determine whether the coal unit is damaged under the tensile stress. If no damage occurs, then the Mohr-Coulomb criterion is used to determine whether the coal unit is subject to shear stress.

The damage variable of coal body unit is expressed by the following formula:

$$D = \begin{cases} 0 & F_1 < 0, F_2 < 0 \\ 1 - \left(\frac{\varepsilon_{t0}}{\varepsilon_t}\right)^2 & F_1 = 0, dF_1 > 0 \\ 1 - \left(\frac{\varepsilon_{c0}}{\varepsilon_c}\right)^2 & F_2 = 0, dF_2 > 0, \end{cases} \quad (17)$$

where ε_t is the maximum principal strain of coal body unit; ε_c is the minimum principal strain of coal body unit; ε_{t0} is the ultimate tensile strain of coal body when tensile damage occurs to coal body unit; and ε_{c0} is the ultimate compressive strain of coal body when shear damage occurs to coal body unit.

Porosity and permeability, as the key parameters of coal seam gas migration in the coal body during the extraction process, are closely related to the stress and the inherent material characteristics of coal body. The porosity in coal matrix can be expressed as follows [25]:

$$\varphi_m = \frac{1}{(1 + S)} [\varphi_{m0}(1 + S_0) + \alpha_m(S - S_0)], \quad (18)$$

where $S = \varepsilon_v + p_m/K_s - \varepsilon_a$, $S_0 = \varepsilon_{v0} + p_{m0}/K_s - \varepsilon_{a0}$, ε_v is the volumetric strain of coal, and the subscript "0" represents the initial value.

From formula (9), the volumetric strain of coal matrix is obtained as follows:

$$\varepsilon_v = -\frac{1}{K} (\bar{\sigma} - \alpha_m p_m - \alpha_f p_f) + \varepsilon_a \quad (19)$$

where $\bar{\sigma}$ is the average principal stress, $\bar{\sigma} = (\sigma_{11} + \sigma_{22} + \sigma_{33})/3$.

Fracture and porosity can be defined as [34]

$$\varphi_f = \varphi_{f0} - \frac{3\varphi_{f0}(\Delta\varepsilon_a - \Delta\varepsilon_v)}{\varphi_{f0} + 3K_f/K}, \quad (20)$$

where K_f is the improved crack stiffness, GPa, and b is the crack width, m.

The relationship between permeability ratio and porosity ratio of coal seam fracture is expressed by cubic law:

$$\frac{k}{k_0} = \left(\frac{\phi_f}{\phi_{f0}}\right)^3. \quad (21)$$

By introducing equation (19) into equation (20), the permeability model of coal body in elastic deformation stage can be obtained [17]:

$$k = k_0 \left(1 - \frac{3(\alpha_T \Delta T + \Delta\varepsilon_a - \Delta\varepsilon_v)}{\phi_{f0} + 3K_f/K}\right)^3, \quad (22)$$

where k_0 is the initial permeability, m^2 .

The relationship between the sudden increase coefficient of coal permeability and the damage variable is exponential [42]:

$$\xi = e^{\alpha_D D}, \quad (23)$$

where α_D is the damage coefficient and D is the damage variable.

Considering the pore pressure and damage evolution, the permeability model of coal body damage and failure stage can be obtained:

$$k_d = k_0 \left[1 - \frac{3(\alpha_T \Delta T + \Delta \varepsilon_a - \Delta \varepsilon_v)}{\varphi_{f0} + 3K_f/K} \right]^3 e^{\alpha_D D}. \quad (24)$$

Equations (5), (8), (12), (17), and (24) are combined, that is, the multifield and multiphase coupling model of coal seam gas extraction. It can be solved by finite element software to simulate the process of coal seam gas extraction with large-diameter borehole in soft coal seam.

3. Simulations of Stress Relief Enhanced Permeability and Gas Extraction in Soft Coal Seam

3.1. Solution Conditions for Numerical Simulation. The working face 3205 of Zhongxing Coal Mine of Fenxi Mining Industry Co., Ltd. mines in No.2 coal seam located in Shanxi formation of Lower Permian. The tested results show that the firmness coefficient of No.2 coal seam is 0.22~0.41, tensile strength is 0.11~0.35 MPa, uniaxial compressive strength is 4.6~7.8 MPa, elastic modulus is 1.8~3.5 GPa, and permeability is about $0.5 \times 10^{-17} \sim 1.26 \times 10^{-17} \text{ m}^2$. The No.2 coal seam is a kind of coking coals with the maximum reflectance of vitrinite of 1.55~1.81. According to the above parameters, the coal seam belongs to soft low-permeability coal seam. Considering the geological conditions (coal seam, roof, and floor), a two-dimensional geometric model for numerical simulations is established, as shown in Figure 2.

The size of the model is $20 \text{ m} \times 7 \text{ m}$, in which the coal seam thickness is 2 m, the floor thickness is 2.5 m, and the roof thickness is 2.5 m. Sliding boundary conditions are adopted for the bottom and surrounding boundaries of the model. The gravity load of overburden is 15 MPa on the top, calculated by the buried depth of 625 m and the rock mass density of 2400 kg/m^3 .

Three large-diameter boreholes with a diameter of 300 mm and a spacing of 5 m are set up in the coal seam. The geometric model is meshed. The complete mesh contains 30771 domains, 2698 boundaries, and 337 edges.

3.2. Mathematic Model Verification. Figure 3 shows the gas flux of both numerical simulation and field measured data from the working face 3205 in Zhongxing Coal Mine. With the increase of time, the gas flow first decreases rapidly and then slowly, and the trend of the two cases is basically the same. During the initial period 80 days, the numerical simulation results were lower than the field test results. But, after extracting 80 days, the numerical simulation results were higher than the field test results.

Overall, a slight deviation of the gas flux is apparent between observations and model results, which may result from the anisotropy and heterogeneity of coal seams. However, the modelling and measured results are generally in good agreement.

3.3. Influence of Borehole Diameter on Stress Relief Enhanced Permeability in Soft Coal. To clarify the influence of borehole diameter on pressure relief and permeability enhancement of broken soft coal seam, the evolution law of elastic modulus,

FIGURE 2: Geometric model of numerical simulation.

FIGURE 3: Comparison between simulated and measured gas flux.

damage zone, permeability, and stress in soft coal seam was simulated and studied by drilling holes with diameters of 94 mm, 133 mm, 200 mm, and 300 mm. In the site of underground coal mine, the commonly used drilling diameter is 94 mm and 133 mm. The diameter of large-diameter borehole experimented in Zhongxing Coal Mine is 300 mm. For comparison, the diameter of 200 mm as a transition is added. Hence, the borehole diameter scheme (94-133-200-300 mm) is selected.

Figure 4 shows the distribution of elastic modulus of soft coal seam with different borehole diameters. With the increase of the borehole diameter, the elastic modulus around the borehole decreases. When the borehole diameter is 94 mm, the damage area in coal mass around the borehole is not obvious. When the borehole diameter increases to 133 mm, the coal body around the borehole begins to appear damage area, which is concentrated on both sides of the borehole. When the borehole diameter is 200 mm, the damage area is further expanded, which is equivalent to the diameter of the drilling hole. When the drilling diameter increases to 300 mm, the damage area around the borehole basically exceeds the borehole diameter.

In Figure 5, the value of damage variable in coal seam is in the range of 0~1. In the position far away from the

FIGURE 4: Distribution of elastic modulus of soft coal seam with different borehole diameters.

FIGURE 5: Distribution of damage area in soft coal seam with different borehole diameters.

borehole, the coal seam will not be damaged. However, in the area near the borehole, the in situ stress will produce stress concentration in the surrounding rock of the borehole, and the coal seam will suffer tensile and shear failure.

The area near the middle borehole (5 m in length and 2 m in height) is selected as the research object to analyze the distribution law of stress and permeability of coal around a single borehole, as shown in Figure 6.

Figure 7 displays the distribution of the maximum principal stress in the coal mass around a single borehole. It can be found that the stress of coal seam is redistributed due to the emergence of boreholes, and the “three zones” distribution law of stress appears. The stress decreases near the borehole-stress relief zone, and the stress rise zone appears at the edge of the stress relief zone. The stress in the coal body far away from the borehole does not change significantly, which is the original stress area. With the increase of borehole diameter, the range of the maximum principal stress decreasing zone in coal mass around the borehole is further expanded. This indicates that the larger the borehole diameter, the better the pressure relief effect of coal body.

Figure 8 presents the permeability distribution law of soft coal seam with borehole diameters of 94 mm, 133 mm,

FIGURE 6: Research area of single borehole broken soft coal seam.

200 mm, and 300 mm. When the borehole diameter is 94 mm, the coal permeability around the borehole is almost the original permeability. When the borehole diameter increases to 133 mm, the permeability begins to increase in the coal body near the borehole. When the borehole diameter increases to 200 mm and 300 mm, the area of enhanced permeability further expands. It can be found that the spatial distribution of enhanced permeability area is shear band, which indicates that shear failure zone appears around the large-diameter borehole, and its permeability rises sharply.

FIGURE 7: Distribution of maximum principal stress in soft coal seam with different borehole diameters.

FIGURE 8: Distribution of permeability in soft coal seam with different borehole diameters.

This opens up the transport channel of coal seam gas and is conducive to the rapid extraction of coal seam gas.

When compared Figure 5 with Figure 8, we can see the damage area and permeability increasing area both increase with the increase of borehole diameter. The damage area nearly overlaps with the permeability increasing area. The larger the damage value, the higher the permeability increasing magnitude. This result is consistent with formula (24). The permeability variation will largely influence the gas seepage law within the tight coal reservoir. The gas seepage around the large-diameter borehole will become more severe.

3.4. Effect of Borehole Diameter on Gas Extraction Efficiency in Soft Coal Seam. According to the results of stress relief and permeability enhancement of large-diameter borehole with 300 mm in diameter in soft coal seam, the negative pressure of borehole wall was set as 20 kPa, and the laws of gas

pressure, gas content, gas flow, and cumulative extraction volume during 120 days of gas extraction were simulated and analyzed.

Figure 9 shows the gas pressure distribution in soft coal mass after 120 days of extraction with different borehole diameters. It can be seen that the larger the borehole diameter is, the larger the scope of gas pressure reduction is, as well as the better the drainage effect.

The data of gas pressure during 120 days of extraction with different borehole diameters on A-B line are extracted, and these data is drawn in the curve of Figure 10. The larger borehole diameter corresponds to greater decrease of gas pressure. After 120 days of extraction, the maximum gas pressure in coal seam between the two boreholes was 0.462 MPa, 0.432 MPa, 0.369 MPa, and 0.338 MPa, respectively, which decreased by 39.21%, 43.15%, 51.44%, and 55.52% compared with the original 0.76 MPa.

FIGURE 9: Gas pressure of coal seam after different diameters in soft coal seam (120 days).

FIGURE 10: Gas pressure curve on A-B line in soft coal seam after 120 days' extraction with different borehole diameters.

The contour of gas pressure distribution in soft coal seam after 120 days of extraction under different borehole diameters (94 mm, 133 mm, 200 mm, and 300 mm) is shown in Figure 11. The gas content of $8 \text{ m}^3/\text{t}$ is taken as the standard of effective extraction. With the increase of borehole diameter, the effective extraction range increases. When the diameter of boreholes is 94 mm, 133 mm, and 200 mm, there is a nonstandard extraction area between the two boreholes, and the area decreases with the increase of boreholes. When the borehole diameter increases to 300 mm, the substandard area between the two boreholes gradually disappears. It indi-

cates that after 120 days of extraction, the gas extraction efficiency can be improved by using the borehole diameter of 300 mm, and the gas content can be reduced below the limit value, thus eliminating the danger of coal seam outburst.

Figure 12 compares the changes of effective extraction area in different borehole diameters. When the extraction time is 60 days, the effective extraction areas of 94 mm, 133 mm, 200 mm, and 300 mm are 3.05 m^2 , 6.71 m^2 , 12.72 m^2 , and 17.06 m^2 , respectively. The effective extraction area of borehole diameter of 300 mm is 5.59 times, 2.54 times, and 1.34 times of that of 94 mm, 133 mm, and 200 mm, respectively. When the extraction time reaches 120 days, the effective extraction area of 94 mm, 133 mm, 200 mm, and 300 mm are 11.09 m^2 , 17.42 m^2 , 23.65 m^2 , and 27.11 m^2 , respectively. The effective extraction area of borehole diameter of 300 mm is 2.44 times, 1.55 times, and 1.14 times of that of 94 mm, 133 mm, and 200 mm, respectively.

The variation of gas content with time when the borehole diameter is 94 mm is shown in Figure 13. Reference points C (7.5 m, 3.5 m) and D (8.75 m, 3.5 m) are located between boreholes 1 and 2. The gas content of reference points C and D decreases with the increase of extraction time. Because point D is close to the extraction borehole, the pressure drop funnel formed by the borehole reaches point D earlier than point C, and the gas content decreases more rapidly. For the extraction borehole with diameter of 94 mm, the gas content at reference points C and D is $6.55 \text{ m}^3/\text{t}$ and $6.05 \text{ m}^3/\text{t}$, respectively, when extracting for 120 days. The gas predrainage rate of coal mining face must be higher than 30%. Through calculation, the gas content in coal seam must be reduced to $6.2 \text{ m}^3/\text{t}$, which is regarded as the standard of gas drainage. At the position of reference point C, the predrainage of coal seam gas is substandard. The closer to the borehole, the easier the gas drainage is to reach the standard, which is consistent with the situation on site.

The variation of gas content with time when the borehole diameter is 133 mm is shown in Figure 14. The gas content of

FIGURE 11: Gas content in soft coal seam after different borehole diameters (120 days).

FIGURE 12: Variation of effective extraction area with different diameter boreholes.

reference points C and D decreases with the increase of extraction time. For the borehole diameter of 133 mm, the gas content at reference point C is $6.26 \text{ m}^3/\text{t}$, and that at reference point D is $5.72 \text{ m}^3/\text{t}$ when extracting for 120 days. At the position of reference point C, the predrainage of coal seam gas is substandard.

The variation of gas content with time when the borehole diameter is 200 mm is shown in Figure 15. The gas content of reference points C and D decreases with the increase of extraction time. For the borehole diameter of 200 mm, the gas content of reference point C at 120 days is $5.62 \text{ m}^3/\text{t}$, and that of reference point D is $4.89 \text{ m}^3/\text{t}$. These all meet the standard of less than $6.2 \text{ m}^3/\text{t}$.

Figure 16 shows the change of gas content with time when the borehole diameter is 300 mm. Consistent with the

previous results, the gas content of reference points C and D decreases with the increase of extraction time. After 120 days of extraction, the gas content of reference points C and D are $5.29 \text{ m}^3/\text{t}$ and $4.43 \text{ m}^3/\text{t}$, respectively, which meet the standard of less than $6.2 \text{ m}^3/\text{t}$.

Figures 17 and 18 show the variation law of gas flow rate and cumulative gas extraction volume with time under different borehole diameters at borehole length of 100 m.

As shown in Figure 17, the velocity of gas flow in coal seam is fast in the initial stage of extraction. The maximum gas flow rate of 94 mm borehole is $0.05 \text{ m}^3/\text{min}$, while that of 133 mm, 200 mm, and 300 mm is $0.068 \text{ m}^3/\text{min}$, $0.094 \text{ m}^3/\text{min}$, and $0.125 \text{ m}^3/\text{min}$. The average gas flow of 94 mm borehole is $0.0230 \text{ m}^3/\text{min}$, and the average gas flow of 133 mm, 200 mm, and 300 mm is $0.0266 \text{ m}^3/\text{min}$, $0.0324 \text{ m}^3/\text{min}$, and $0.0354 \text{ m}^3/\text{min}$, respectively, which are 1.156 times, 1.408 times, and 1.539 times of the average gas flow of 94 mm borehole.

With the increase of time, the pressure of coal seam pressure decreases, and the pressure gradient between coal seam and borehole wall decreases. The moving motivation of coal seam gas weakens, and the gas flow slows down. After 120 days of extraction, the coal seam gas flow is between $0.0154 \text{ m}^3/\text{min}$ and $0.0168 \text{ m}^3/\text{min}$. In Figure 18, the cumulative gas extraction increases with time, increases rapidly at the initial stage, and then increases linearly. After 120 days of pumping, the gas extraction volumes with borehole diameters of 94 mm, 133 mm, 200 mm, and 300 mm are 3980 m^3 , 4596 m^3 , 5822 m^3 , and 6449 m^3 , respectively.

The above research shows that gas extraction using large-diameter borehole can effectively reduce the gas pressure and gas content in the coal seam by increasing the gas extraction rate and gas volume. The efficiency of the gas preextraction in soft coal seam can be greatly improved, and the time cost of gas extraction in coal mine is saved as well. Large-diameter borehole effectively alleviates the imbalance among coal mining, roadway advancing, and gas extraction.

FIGURE 13: Variation of gas content with time when borehole diameter is 94 mm.

FIGURE 15: Variation of gas content with time when borehole diameter is 200 mm.

FIGURE 14: Variation of gas content with time when borehole diameter is 133 mm.

FIGURE 16: Variation of gas content with time when borehole diameter is 300 mm.

4. Conclusions

- (1) We established a damage-stress-seepage coupling model for large-diameter borehole gas extraction in soft coal seam, which contains governing equations of gases sorption and transport, coal deformation, and damage, reflecting the coupling responses between gas and coal seam
- (2) The proposed damage-stress-seepage coupling model is used to simulate the gas drainage large-diameter borehole through roadway. Distributions of elastic modulus, damage area, and maximum principal

stress in soft coal seam with different borehole diameters are analyzed. Shear failure zone appears around the large-diameter borehole, and its permeability rises sharply. This opens up the gas transport channel and is conducive to the rapid extraction

- (3) Gas extraction with different borehole diameters including 94 mm, 133 mm, 200 mm, and 300 mm is simulated. The gas pressure and gas content on cutting face and A-B line in soft coal seam are presented, as well as the effective extraction area and cumulative gas extraction volume. Results show that gas extraction using large-diameter borehole (300 mm) can

FIGURE 17: Variation of gas flow under different borehole diameters.

FIGURE 18: Variation of cumulative gas extraction volume under different borehole diameters.

greatly improve the efficiency of the gas preextraction in soft coal seam by increasing gas extraction rate.

In the future, additional influencing factors may be considered in the proposed mathematic model, such as water content and temperature varying within coal seam. It will be more appropriate to use discrete element method to calculate the broken coal and gas migration.

Data Availability

The data used in this article were from the simulation results by COMSOL Mutiphsysics. The equations were written as

COMSOL codes independently to conduct these simulations. The data are available from the corresponding author upon request.

Conflicts of Interest

The authors declare no competing financial interest.

Acknowledgments

The authors would like to thank all editors and anonymous reviewers for their comments and suggestions. This research was financially supported by the National Science and Technology Major Project (2016ZX05067-005-002).

References

- [1] K. Noack, "Control of gas emissions in underground coal mines," *International Journal of Coal Geology*, vol. 35, no. 1-4, pp. 57-82, 1998.
- [2] F. Bertrand, B. Cerfontaine, and F. Collin, "A fully coupled hydro-mechanical model for the modeling of coalbed methane recovery," *Journal of Natural Gas Science and Engineering*, vol. 46, pp. 307-325, 2017.
- [3] T. Xia, F. Zhou, J. Liu, and F. Gao, "Evaluation of the pre-drained coal seam gas quality," *Fuel*, vol. 130, pp. 296-305, 2014.
- [4] J. Wen, W. Cheng, L. Chen, S. Shi, and Z. Wen, "A study of the dynamic movement rule of overlying strata combinations using a short-wall continuous mining and full-caving method," *Energy Science & Engineering*, vol. 7, no. 6, pp. 2984-3004, 2019.
- [5] C. Fan, S. Li, D. Elsworth, J. Han, and Z. Yang, "Experimental investigation on dynamic strength and energy dissipation characteristics of gas outburst-prone coal," *Energy Science & Engineering*, vol. 8, no. 4, pp. 1015-1028, 2020.
- [6] T. Lu, H. Yu, T. Zhou, J. Mao, and B. Guo, "Improvement of methane drainage in high gassy coal seam using waterjet technique," *International Journal of Coal Geology*, vol. 79, no. 1-2, pp. 40-48, 2009.
- [7] B. Lin, F. Yan, C. Zhu et al., "Cross-borehole hydraulic slotting technique for preventing and controlling coal and gas outbursts during coal roadway excavation," *Journal of Natural Gas Science and Engineering*, vol. 26, pp. 518-525, 2015.
- [8] F. Gao, Y. Xue, Y. Gao, Z. Zhang, T. Teng, and X. Liang, "Fully coupled thermo-hydro-mechanical model for extraction of coal seam gas with slotted boreholes," *Journal of Natural Gas Science and Engineering*, vol. 31, pp. 226-235, 2016.
- [9] Q. Huang, S. Liu, G. Wang, and W. Cheng, "Evaluating the changes of sorption and diffusion behaviors of Illinois coal with various water-based fracturing fluid treatments," *Fuel*, vol. 283, p. 118884, 2021.
- [10] C. Fan, S. Li, M. Luo, Z. Yang, and T. Lan, "Numerical simulation of hydraulic fracturing in coal seam for enhancing underground gas drainage," *Energy Exploration & Exploitation*, vol. 37, no. 1, pp. 166-193, 2019.
- [11] S. Yu, J. Bo, and Q. Meijun, "Molecular dynamic simulation of self-and transport diffusion for CO₂/CH₄/N₂ in low-rank coal vitrinite," *Energy & Fuels*, vol. 32, no. 3, pp. 3085-3096, 2018.
- [12] L. Wang, Y. Cheng, C. Ge et al., "Safety technologies for the excavation of coal and gas outburst-prone coal seams in deep

- shafts," *International Journal of Rock Mechanics and Mining Sciences*, vol. 57, pp. 24–33, 2013.
- [13] T. Liu, B. Lin, X. Fu et al., "Experimental study on gas diffusion dynamics in fractured coal: a better understanding of gas migration in in-situ coal seam," *Energy*, vol. 195, p. 117005, 2020.
 - [14] T. Liu and B. Lin, "Time-dependent dynamic diffusion processes in coal: model development and analysis," *International Journal of Heat and Mass Transfer*, vol. 134, pp. 1–9, 2019.
 - [15] S. L. Song, X. S. Liu, Y. L. Tan, D. Y. Fan, Q. Ma, and H. L. Wang, "Study on failure modes and energy evolution of coal-rock combination under cyclic loading," *Shock and Vibration*, vol. 2020, Article ID 5731721, 16 pages, 2020.
 - [16] T. Lan, C. Fan, J. Han, H. Zhang, and J. Sun, "Controlling mechanism of rock burst by CO₂ fracturing blasting based on rock burst system," *Shock and Vibration*, vol. 2020, Article ID 8876905, 9 pages, 2020.
 - [17] C. Fan, D. Elsworth, S. Li, L. Zhou, Z. Yang, and Y. Song, "Thermo-hydro-mechanical-chemical couplings controlling CH₄ production and CO₂ sequestration in enhanced coalbed methane recovery," *Energy*, vol. 173, pp. 1054–1077, 2019.
 - [18] C. Fan, M. Luo, S. Li, H. Zhang, Z. Yang, and Z. Liu, "A thermo-hydro-mechanical-chemical coupling model and its application in acid fracturing enhanced coalbed methane recovery simulation," *Energies*, vol. 12, no. 4, p. 626, 2019.
 - [19] C. Fan, S. Li, M. Luo, L. Zhou, H. Zhang, and Z. Yang, "Effects of N and S functionalities on binary gas co-adsorption on a coal macromolecule," *Energy & Fuels*, vol. 33, no. 5, pp. 3934–3946, 2019.
 - [20] B. Huo, X. Jing, C. Fan, and Y. Han, "Numerical investigation of flue gas injection enhanced underground coal seam gas drainage," *Energy Science & Engineering*, vol. 7, no. 6, pp. 3204–3219, 2019.
 - [21] J. Liu, L. Z. Xie, D. Elsworth, and Q. Gan, "CO₂/CH₄ competitive adsorption in shale: implications for enhancement in gas production and reduction in carbon emissions," *Environmental Science & Technology*, vol. 53, no. 15, pp. 9328–9336, 2019.
 - [22] J. Liu, L. Z. Xie, Y. B. Yao, Q. Gan, P. Zhao, and L. H. Du, "Preliminary study of influence factors and estimation model of the enhanced gas recovery stimulated by carbon dioxide utilization in shale," *ACS Sustainable Chemistry & Engineering*, vol. 7, no. 24, pp. 20114–20125, 2019.
 - [23] Q. Huang, S. Liu, G. Wang, B. Wu, Y. Yang, and Y. Liu, "Gas sorption and diffusion damages by guar-based fracturing fluid for CBM reservoirs," *Fuel*, vol. 251, pp. 30–44, 2019.
 - [24] Q. Huang, S. Liu, G. Wang, B. Wu, and Y. Zhang, "Coalbed methane reservoir stimulation using guar-based fracturing fluid: a review," *Journal of Natural Gas Science and Engineering*, vol. 66, pp. 107–125, 2019.
 - [25] Z. Pan, L. D. Connell, and M. Camilleri, "Laboratory characterisation of coal reservoir permeability for primary and enhanced coalbed methane recovery," *International Journal of Coal Geology*, vol. 82, no. 3–4, pp. 252–261, 2010.
 - [26] T. Liu, S. Liu, B. Lin et al., "Stress response during in-situ gas depletion and its impact on permeability and stability of CBM reservoir," *Fuel*, vol. 266, p. 117083, 2020.
 - [27] Y. Lu, Y. Liu, X. Li, and Y. Kang, "A new method of drilling long boreholes in low permeability coal by improving its permeability," *International Journal of Coal Geology*, vol. 84, no. 2, pp. 94–102, 2010.
 - [28] Y. Gao, B. Lin, W. Yang, Z. Li, Y. Pang, and H. Li, "Drilling large diameter cross-measure boreholes to improve gas drainage in highly gassy soft coal seams," *Journal of Natural Gas Science and Engineering*, vol. 26, pp. 193–204, 2015.
 - [29] Y. J. Zhao, S. R. Xie, B. G. Wen, H. D. Guo, and S. J. Yuan, "Gas drainage technology by 1000m long and large diameter roof boreholes in high gas coal seam group," *Journal of China Coal Society*, vol. 34, no. 6, pp. 797–801, 2009.
 - [30] C. L. Dong, D. Z. Tian, J. G. Zhao, and F. Lan, "Application and development on drill rod matched for large diameter and directional long borehole in underground coal mine," *Coal Science and Technology*, vol. 46, no. 9, pp. 196–201, 2018.
 - [31] M. G. Hua, K. W. Wang, Y. S. Fu, and G. T. Fu, "Study on technology of controlling upper corner gas by super-large diameter borehole," *Coal Technology*, vol. 39, no. 7, pp. 122–125, 2020.
 - [32] L. Yuan, H. Guo, P. Li, Y. P. Liang, and B. C. Miao, "Theory and technology of goaf gas drainage with large-diameter surface boreholes," *Journal of China Coal Society*, vol. 38, no. 1, pp. 1–8, 2013.
 - [33] H. Gao and H. W. Yang, "Super large diameter borehole gob gas extraction technology," *Coal Science and Technology*, vol. 47, no. 2, pp. 77–81, 2019.
 - [34] G. Wang, K. Wang, S. Wang, D. Elsworth, and Y. Jiang, "An improved permeability evolution model and its application in fractured sorbing media," *Journal of Natural Gas Science and Engineering*, vol. 56, pp. 222–232, 2018.
 - [35] G. Wang, X. Qin, J. Shen, Z. Zhang, D. Han, and C. Jiang, "Quantitative analysis of microscopic structure and gas seepage characteristics of low-rank coal based on CT three-dimensional reconstruction of CT images and fractal theory," *Fuel*, vol. 256, p. 115900, 2019.
 - [36] R. Shi, J. Liu, M. Wei, D. Elsworth, and X. Wang, "Mechanistic analysis of coal permeability evolution data under stress-controlled conditions," *International Journal of Rock Mechanics and Mining Sciences*, vol. 110, pp. 36–47, 2018.
 - [37] J. Liu, L. Xie, B. He, Q. Gan, and P. Zhao, "Influence of anisotropic and heterogeneous permeability coupled with in-situ stress on CO₂ sequestration with simultaneous enhanced gas recovery in shale: quantitative modeling and case study," *International Journal of Greenhouse Gas Control*, vol. 104, p. 103208, 2021.
 - [38] C. Zheng, M. Kizil, Z. Chen, and S. Aminossadati, "Effects of coal damage on permeability and gas drainage performance," *International Journal of Mining Science and Technology*, vol. 27, no. 5, pp. 783–786, 2017.
 - [39] G. Bai, Y. H. Jiang, X. M. Li et al., "Quantitative experimental investigation of CO₂ enhancement of the desorption rate of adsorbed CH₄ in coal," *Energy Reports*, vol. 6, pp. 2336–2344, 2020.
 - [40] G. Bai, X. K. Zeng, X. M. Li, X. H. Zhou, Y. T. Cheng, and J. S. Linghu, "Influence of carbon dioxide on the adsorption of methane by coal using low-field nuclear magnetic resonance," *Energy & Fuels*, vol. 34, no. 5, pp. 6113–6123, 2020.
 - [41] T. Liu, B. Lin, X. Fu, and C. Zhu, "Modeling air leakage around gas extraction boreholes in mining-disturbed coal seams," *Process Safety and Environmental Protection*, vol. 141, pp. 202–214, 2020.
 - [42] T. Liu, B. Lin, X. Fu, and S. Liu, "A new approach modeling permeability of mining-disturbed coal based on a conceptual model of equivalent fractured coal," *Journal of Natural Gas Science and Engineering*, vol. 79, p. 103366, 2020.

- [43] C. Fan, S. Li, H. Zhang, and Z. Yang, “Rational boreholes arrangement of gas extraction from unloaded coal seam,” *Advances in Civil Engineering*, vol. 2018, Article ID 1501860, 9 pages, 2018.
- [44] P. Zhao, H. Liu, S. Li et al., “Exploring the adsorption and diffusion characteristics of tectonic coal at different mass ratios based on the specific surface Gibbs function,” *Powder Technology*, vol. 376, pp. 604–611, 2020.