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

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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 pre-extraction 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 considered 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]:

\[ m_m = \phi_m \rho_g + V_{sg} \rho_{g/s}, \]

where \( \phi_m \) is porosity in coal matrix; \( \rho_g \) is the density of coal seam gas, kg/m^3; \( V_{sg} \) is gas content of adsorbed coal seam gas, m^3/kg; \( \rho_j \) is the density of coal, kg/m^3; and \( \rho_{g/s} \) is the density of coal seam gas in standard state, kg/m^3.

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

\[ \rho_g = \frac{M_g}{RT}, \]

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):

\[ V_{sg} = \frac{V_L p_m}{P_L + p_m}, \]

where \( V_L \) is Langmuir volume constant, m^3/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]:
∂ \frac{\partial 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 \( \tau \) 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]:

\[
\frac{\partial}{\partial t} \left( \frac{V_i p_m}{P_L + p_m} \rho_s M_g \frac{P_m}{RT_s} + \varphi \frac{M_g}{RT} p_m \right) = - \frac{M_g}{\tau RT} (p_m - p_{fg}).
\]  

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

\[
\frac{\partial}{\partial t} \left( \varphi_f \rho_f \frac{p_f}{P_f} \right) + \nabla \cdot \left( \rho_f \bar{q}_g \right) = \left( 1 - \varphi_f \right) \frac{M_g}{\tau RT} (p_m - p_{fg}),
\]  

where \( \varphi_f \) is fracture porosity and \( \bar{q}_g \) 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]

\[
\bar{q}_g = - \frac{k}{\mu_g} \left( 1 + \frac{b_1}{p_{fg}} \right) \nabla p_{fg},
\]  

where \( k \) is the absolute permeability of fracture, m\(^2\); \( \mu_g \) 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:

\[
\frac{\partial}{\partial t} \left( \varphi_f \frac{M_g}{RT} p_{fg} \right) + \nabla \cdot \left( \frac{M_g p_{fg} + b_1}{RT} \frac{k}{\mu_g} \nabla p_{fg} \right) = \left( 1 - \varphi_f \right) \frac{M_g}{\tau RT} (p_m - p_{fg}).
\]  

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]:

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

where \( \delta_{ij} \) is the Kronecker symbol; \( D \) is equivalent coal elastic modulus, GPa; \( G \) is coal shear modulus, GPa; \( K \) is coal bulk modulus, GPa; \( K_s = \frac{E_s}{3(1 - 2 \nu)} \) is coal skeleton bulk modulus, GPa; \( E_s \) is coal skeleton elastic modulus, GPa; \( k_n \) is fracture stiffness; GPa; \( \nu \) is Poisson’s ratio; \( \alpha_m \) and \( \alpha_f \) 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]:

\[
\varepsilon_a = \alpha_{sg} V_{sg},
\]  

where \( \alpha_{sg} \) 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:

\[
\begin{aligned}
\varepsilon_{ij} &= \frac{1}{2} (u_{ij} + u_{ji}), \\
\sigma_{ij} + F_i &= 0,
\end{aligned}
\]  

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

$$Gx_{ij} + \frac{G}{1-\nu} x_{ij;kl} - \alpha_m p_{m,i} - \alpha_i p_{j,i} - K\epsilon_{ii} + F_i = 0. \quad (12)$$

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

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

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]:

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

$$F_2 = -\sigma_3 + \sigma_1 \left(1 + \sin \theta \over 1 - \sin \theta \right) - \sigma_c = 0, \quad (16)$$

where $\sigma_1$ is the maximum principal stress, MPa; $\sigma_3$ is the minimum principal stress, MPa; $\sigma_t$ and $\sigma_c$ are the uniaxial tensile strength and uniaxial compressive strength of coal, MPa; $\theta$ 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:

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

where $\epsilon_t$ is the maximum principal strain of coal body unit; $\epsilon_o$ is the minimum principal strain of coal body unit; $\epsilon_n$ is the ultimate tensile strain of coal body when tensile damage occurs to coal body unit; and $\epsilon_o$ 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]:

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

where $S = \epsilon_v + p_m/K_s - \epsilon_o$, $S_0 = \epsilon_{vo} + p_{m0}/K_s - \epsilon_{o0}$, $\epsilon_v$ 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:

$$\epsilon_v = -\frac{1}{K} \left( \sigma - \alpha_m p_m - \alpha_i p_i \right) + \epsilon_a \quad (19)$$

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

Fracture and porosity can be defined as [34]

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

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:

$$k/k_0 = \left( \frac{\varphi_f}{\varphi_{f0}} \right)^3 \quad (21)$$

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

$$k = k_0 \left( 1 - \frac{3(\alpha_T \Delta T + \Delta \epsilon_a - \Delta \epsilon_v)}{\varphi_{f0} + 3K_f/K} \right)^3 \quad (22)$$

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 $\alpha_D$ 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:
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 $5 \times 10^{-17} \sim 1.26 \times 10^{-17} \text{m}^2$. 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 $20 \times 7 \text{m}$, 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, 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...
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, 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.
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.
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 m³/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 indicates 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 m², 6.71 m², 12.72 m², and 17.06 m², 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 m², 17.42 m², 23.65 m², and 27.11 m², 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 m³/t and 6.05 m³/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 m³/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
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 m³/t, and that at reference point D is 5.72 m³/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 m³/t, and that of reference point D is 4.89 m³/t. These all meet the standard of less than 6.2 m³/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 m³/t and 4.43 m³/t, respectively, which meet the standard of less than 6.2 m³/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 m³/min, while that of 133 mm, 200 mm, and 300 mm is 0.068 m³/min, 0.094 m³/min, and 0.125 m³/min. The average gas flow of 94 mm borehole is 0.0230 m³/min, and the average gas flow of 133 mm, 200 mm, and 300 mm is 0.0266 m³/min, 0.0324 m³/min, and 0.0354 m³/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 m³/min and 0.0168 m³/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 m³, 4596 m³, 4596 m³, and 6449 m³, 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.
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...
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 Mutiphysics. 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.

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