A novel in-seam borehole hydraulic flushing gas extraction technology in the heading face: Enhanced permeability mechanism, gas flow characteristics, and application

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Abstract

The heading face in soft and low-permeability coal seams is one of the most high-risk areas for Chinese coal and gas miners because of the number of outburst-related accidents. To prevent and control these disasters, the in-seam borehole gas extraction technology is widely used because of its low construction cost. Unfortunately, few studies consider its gas extraction efficiency.

Thus, a new in-seam borehole hydraulic flushing (ISBHF) gas extraction technology is proposed in this paper, where the hydraulic flushing technology is used to enhance the gas extraction of in-seam boreholes. Based on the engineering background in the Xinjing coal mine, a detailed study of this new technology is conducted. First, we model the permeability-increasing mechanism of this technology and the gas flow characteristics of the hydraulic flushing boreholes using a finite-element method. During this process, the strain-softening behavior of the coal mass and the effect of the coal mass failure on the permeability evolution are considered. Second, a reasonable gas extraction scheme is designed, which considers the divergent characteristics of boreholes in the heading face and the interactions among multiple boreholes in the gas extraction process. Finally, the gas extraction scheme is implemented at the S5 intake airflow roadway to verify the simulation results and to evaluate the efficiency of this technology.

The field test results are consistent with the simulation results, which validates our model. Moreover, using this new technology, the number of gas extraction boreholes in the heading face decreased by 50%. Conversely, the gas extraction-based concentration and flow increased 10- and 6-fold, respectively, which results in a 65% decrease in gas extraction time and a 100% increase in monthly excavation length of the coal mine roadway. These results indicate that this new technology is a promising method to achieve efficient gas extraction and rapid excavation in the heading face of soft and low-permeability coal seams.

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1. Introduction

Coal-bed methane (CBM), which is an efficient and clean source of energy (Karacan et al., 2011; Moore, 2012; Petrov and Tanev, 2015), is abundant in China (Su et al., 2005). However, unlike other nations, most of the gas-producing coal seams in China are soft and have low permeability (Liu et al., 2014; Lu et al., 2010; Wang et al., 2014a), which limits the CBM production and introduces considerable challenges to coal mine safety and efficiency (Cheng et al., 2012; Jiang et al., 2011; Yao et al., 2016). In the coal industry, coal and gas outburst disasters are usually considered the greatest threat to coal mine safety. Although the mechanisms that cause coal and gas outbursts are still not fully understood by...
scientists (Beamish and Crosdale, 1998; Fan et al., 2017; Shepherd et al., 1981; Sobczyk, 2014; Zhao et al., 2016), the underground stress, gas pressure, and mechanical strength of a coal mass are three main factors generally associated with outburst disasters (Geng et al., 2017; Wang et al., 2013a, 2014b; Xu et al., 2006). As a result, soft and low-permeability coal seams, which are characterized by high gas pressure and low mechanical strength, usually have a greater risk of triggering coal and gas outbursts. Moreover, during the excavation process of coal roadways, the stress state in the coal mass before the heading face significantly changes, which makes the heading face in soft and low-permeability coal seams one of the highest-risk areas for coal and gas outburst accidents (Lin et al., 2015; Lu et al., 2011; Yang et al., 2014).

Gas extraction is commonly considered a primary measure to control coal and gas outburst accidents. In China, the cross-borehole gas extraction technology and in-seam borehole gas extraction technology are two main technologies used to extract gas from the heading face (Kong et al., 2016; Lin et al., 2015). In the cross-borehole gas extraction technology (Fig. 1a and b), the boreholes are drilled from a rock roadway, which is a comparatively safe method. Moreover, hydraulic flushing (Fig. 1c) (Li et al., 2011; Liu et al., 2016) and the similar hydraulic technologies, such as hydraulic slotting (Lin et al., 2015; Liu et al., 2015b; Shen et al., 2015; Xue et al., 2017) and hydraulic mining (Li, 2014) have been proposed by different scholars to improve its gas extraction efficiency. Using these hydraulic technologies, stress-relief and permeability-increasing can be achieved in the coal surrounding the borehole; as a result, the gas extraction conditions can be significantly improved. However, the construction cost of this gas extraction technology is rather high because an additional rock roadway must be constructed, as shown in Fig. 1.

Unlike the cross-borehole gas extraction technology, in the in-seam borehole gas extraction technology, the gas extraction scope is divided into different cycles with an overlap length of 20 m in the excavation direction of the coal roadway, and the boreholes are directly drilled into the heading face in each cycle (Fig. 2). As a result, the borehole construction is relatively dangerous, and the State Administration of Work Safety (SAWS) has restricted its use in extremely high-risk coal seams (SAWS, 2016). Moreover, the boreholes are divergent because the borehole space (BS) expands in the excavation direction of the coal roadway, which makes the gas extraction much more difficult in the regions far from the heading face. However, in this technology, the rock roadway is unnecessary, which reduces the construction cost. Thus, this technology is considered low-cost when compared with the cross-borehole gas extraction technology. Consequently, most coal mines tend to use this technology in China. Unfortunately, few studies consider its gas extraction efficiency. Thus, a new in-seam borehole hydraulic flushing (ISHBF) gas extraction technology is proposed in this paper, where the hydraulic flushing technology is used to improve the gas extraction efficiency of the in-seam boreholes.

To reasonably design the gas extraction scheme for this new gas extraction technology, the permeability-increasing mechanism of the hydraulic flushing technology and the gas flow characteristics of the hydraulic flushing boreholes should be well understood and modeled. In the past, many similar studies on the cross-borehole hydraulic flushing/slotting technology have been conducted. Yang et al. (2016) and Lu et al. (2011) studied the stress redistribution characteristics in the coal surrounding the hydraulic flushing/slotting boreholes. Gao et al. (2015) analyzed the permeability evolution in the coal surrounding the hydraulic flushing borehole based on the stress redistribution characteristics and divided the surrounding coal into a permeability-increasing zone, a permeability-decreasing zone and an initial-permeability zone. Gao et al. (2016) proposed a coupled thermo-hydro-mechanical model for the gas extraction of the hydraulic slotting borehole, which considered the effects of temperature, coal matrix swelling and effective stress on the permeability. Nevertheless, there are two main shortcomings in the existing studies: (1) elastic perfectly plastic models are widely used, which results in the omission of coal mass strain-softening

Fig. 1. Cross-borehole and cross-borehole hydraulic flushing gas extraction technologies: (a) layout of the rock roadway and drilling field; (b) cross-borehole gas extraction technology and (c) cross-borehole hydraulic flushing technology.

Fig. 2. In-seam borehole gas extraction technology.
behaviors in the post-peak stage, and (2) the permeability models are based on the stress redistribution characteristics but neglect the effect of coal mass failure.

In the numerical simulation process, the mechanical property of the coal and rock masses is described by the mechanical model and related mechanical parameters. As a result, the selection of a reasonable mechanical model is of great importance in the stress and deformation analysis in the coal surrounding the hydraulic flushing borehole. By 687

- **2. Geological background and technology synopsis**

#### 2.1. Geological background

The Yangquan coal field in northeastern Shanxi province is one of the major production bases for coal and CBM in China. The Xining coal mine is located on the western portion of this coal field. Affected by the Taihang uplift in the east and Wutai uplift in the north, the coal mine appears as a monoclinal structure, which slopes to the southwest at a dip angle of approximately 3°–6°. The main coal-bearing stratum has experienced several severe tectonic movements after its formation. Under strong tectonic stress, multiple-periodic low-order fold structures develop in this mine (Fig. 3), which provide good storage conditions for CBM, so the CBM resources are notably rich.

The #3 coal seam, with a thickness of 2.5 m, is one of the primary minable coal seams at the Xining coal mine. The average gas pressure and gas content determined in situ are 1.5 MPa and 12.5 m³/t, respectively; however, its permeability is only approximately 0.011 mD, which indicates a difficult condition for gas extraction. Furthermore, the low mechanical strength, as indicated by the Protodyakonov coefficient of 0.3−0.5, suggests that the #3 coal seam has a considerable risk of outburst; a serious outburst accident occurred in 2005, with an outburst coal mass of 75 t.

#### 2.2. Technology synopsis

The S5 intake airflow roadway (Fig. 3), which is a 5-m-wide coal roadway, is currently under construction in the #3 coal seam. Because the Protodyakonov coefficient of the #3 coal seam is approximately 0.3−0.5, and the buried depth of the S5 intake airflow roadway is approximately 400 m, SAWS enables the use of the in-seam borehole gas extraction technology in the S5 intake airflow roadway (SAWS, 2016). Therefore, the ordinary in-seam borehole gas extraction technology was used in the past, as shown in Fig. 4a. In each gas extraction cycle, 34 gas extraction boreholes were created, each of which had a radius of 0.045 m and a maximum borehole space (MBS) of 2 m, to extract gas from 20 to 80 m before the heading face and from 15 m on both sides of the coal roadway. However, the gas extraction efficiency is rather low, and the outburst forecast predictors usually exceed the critical values during the excavation process, which caused an average monthly excavation length of 20 m in the S5 roadway.

To speed up the excavation of the S5 intake airflow roadway, a new ISBHF gas extraction technology is proposed in this paper. After drilling the in-seam boreholes, a high-pressure-water jet is used to flush the coal surrounding the borehole and to expand the radius of the borehole (RB). By considering the differences in BS, the gas extraction scope could be divided into different sections. Alternatively, RB could be designed uniquely for each individual section. For the convenience of the gas extraction step and field construction, the design of the gas extraction scope is divided into three sections, as shown in Fig. 4b. The BS is the largest in section I, which includes the region 60−80 m before the heading face and the boundary regions on both sides of the gas extraction scope; therefore, this section should be designed to have the largest RB to decrease the gas extraction time. The BS in section II, which is located 40−60 m before the heading face, is smaller than that in section I; therefore, a smaller RB should be designed for this section. The BS is the smallest in section III, which is located 20−40 m before the heading face; therefore, this section should be designed...
to have the smallest RB to reduce the flushing time.

3. Permeability-increasing mechanism and the gas flow characteristics

3.1. Governing equations

3.1.1. Mechanical process

Considering the strain-softening behavior of the coal mass, an elastic-strain softening model is used in this paper. As shown in Fig. 5, the entire stress-strain curve can be divided into an elastic stage, a strain-softening stage, and a residual stage. Correspondingly, the coal surrounding the borehole is divided into an elastic zone, a plastic softening zone, and a plastic residual zone (Cui et al., 2015).

According to An et al. (2013) and Alonso et al. (2003), the equivalent plastic shear strain can be used as the softening parameter to describe the strain-softening process, which is defined as follows (An et al., 2013; Alonso et al., 2003; Hajiabdolmajid and Kaiser, 2003):

\[
\gamma_p = \sqrt{2/3(e_{p1}^2 + e_{p2}^2 + e_{p3}^2)},
\]  

(1)

where \(e_{p1}^2\), \(e_{p2}^2\), and \(e_{p3}^2\) are the principal plastic strains.

At the beginning of the strain-softening stage, the equivalent plastic shear strain is 0. If the equivalent plastic shear strain at the beginning of the residual stage is \(\gamma_p^*\), different stages of the stress-strain curve and the corresponding zones in the coal surrounding the borehole can be divided according to the equivalent plastic shear strains of 0 and \(\gamma_p^*\).

Moreover, according to Pourhosseini and Shabanimashcoor (2014), the strain-softening process is a process that loses the cohesion as the frictional angle remains unchanged. Assuming that the cohesion linearly decreases with the equivalent plastic shear strain, the cohesion value over the entire stress-strain curve can be defined as follows (An et al., 2013; Jaiswal and Shrivastva, 2009):

\[
c = \left\{ \begin{array}{l}
 c_0 - (c_0 - c_r)\gamma_p^p / \gamma_p^r, \quad \gamma_p^p \leq \gamma_p^r, \\
 c_r, \quad \gamma_p^p > \gamma_p^r,
\end{array} \right.
\]  

(2)

where \(c\) represents the cohesion, \(c_0\) represents the initial cohesion in the elastic stage, and \(c_r\) represents residual cohesion.

The Mohr-Coulomb matching DP yield criterion is selected in this paper to evaluate the failure of the coal mass:

\[
F = \sqrt{f_2 + a_{DP}I_1 - k_{DP}},
\]  

(3)

where \(I_1\) represents the first stress invariant, \(f_2\) represents the second stress invariant, \(a_{DP} = \frac{2 \sin \phi}{\sqrt{3(3\sin \phi)^2}}\) and \(k_{DP} = \frac{6 \cos \phi}{\sqrt{3(3\sin \phi)^2}}\).

3.1.2. Permeability evolution model

The permeability is the governing factor for gas flow in the coal seam. In the elastic stage, the permeability follows a negative
exponential function with the changes in volumetric stress (Seidle et al., 1992; Somerton et al., 1975). Therefore, the permeability equation in the elastic zone around the borehole is (An et al., 2013):

$$k_e / k_0 = e^{-Cf \sigma / C_0 D Q}$$

(4)

where $k_e$ represents the permeability in the elastic zone, $k_0$ represents the initial permeability, $C_f$ represents the cleat volume compressibility, and $\sigma$ represents the volumetric stress.

In the post-peak stage, the permeability linearly increases in the strain-softening stage and remains constant in the residual stage (Viete and Ranjith, 2006; Wang and Park, 2002). Thus, An et al. (2013) established a permeability model to describe the permeability evolution of the coal and rock masses in the post-peak stage. According to their model, the permeability in the plastic softening zone and plastic residual zone is expressed in Eqs. (5) and (6), respectively.

$$k_e / k_0 = \frac{1}{1 + \frac{\gamma b}{\gamma b_{1/2}}} \left(1 + \frac{\gamma b_{1/2}}{\gamma b_{1/2}} e^{-Cf \sigma / C_0 D Q} \right)$$

(5)
where \( k_s \) is the permeability in the plastic softening zone, \( k_r \) is the permeability in the plastic residual zone, and \( \xi \) is the jump coefficient of permeability, which indicates the increasing magnitude of the permeability in the post-peak stage. According to the previous study, the permeability can increase by several to dozens of times, and even by 3–4 orders of magnitude in the post-peak stage (Chen et al., 2016; Konecny and Kozusnikova, 2011; Wang and Park, 2002; Wang et al., 2013b).

### 3.1.3. Gas flow

The gas flow in the coal seam is expressed by the mass conservation equation as follows (Kong et al., 2016; Zhang et al., 2008):

\[
\frac{\partial m}{\partial t} + \nabla (\rho_s u) = Q_m.
\]

where \( m \) is the gas content per volume of coal mass (kg/m³), \( t \) is the time variable (s), \( \rho_s \) is the gas density (kg/m³), \( u \) is the seepage velocity (m/s), and \( Q_m \) is the gas source (kg/(m³ s)).

According to previous research, CBM mainly exists in the coal mass in two states: the adsorption state and the free state (Liu et al., 2015a; Wang et al., 2015). As a result, the gas content per volume of coal mass can be expressed as follows:

\[
m = \frac{V_L p}{p + p_l} \rho_c \frac{1}{1 + 0.31 W} \frac{100 - A - W}{100} + \phi \frac{M_c}{RT} p.
\]

(8)

\[
\rho_s = \frac{M_c}{V_M}.
\]

(9)

where \( V_L \) is the maximum adsorption capacity of coal (m³/kg), \( p \) is the gas pressure (MPa), \( p_l \) is the Langmuir pressure constant (MPa), \( \rho_c \) is the coal density (kg/m³), \( \rho_s \) is the gas density at standard conditions (kg/m³), \( W \) is the moisture content of the coal mass (%), \( A \) is the ash content of the coal mass (%), \( \phi \) is the porosity of coal (%), \( M_c \) is the molar mass (16 g/mol for methane), \( R \) is the gas constant \((8.314510 \text{ J/(mol K)})\), \( T \) is the gas temperature (K), and \( V_M \) is the molar volume of methane under standard conditions \((22.4 \text{ L/mol})\).

According to the ideal gas law, the gas density could be expressed as follows:

\[
\rho_g = \frac{M_c}{RT} p.
\]

(10)

In addition, the gas flow in the coal mass obeys Darcy’s law (Kong et al., 2016; Zhang et al., 2008); therefore, the gas seepage velocity can be expressed as follows:

\[
u = -\frac{k}{\mu} \nabla p.
\]

(11)

where \( \mu \) is the kinematic viscosity (Pa s) and \( k \) is the permeability in the coal seam (m²).

By substituting Eqs. (8)–(11) into Eq. (7), we obtain the gas flow equation in the coal surrounding the borehole:

\[
\left( \frac{M_c \phi}{RT} + \frac{M_c \rho_c}{V_M} \frac{1}{1 + 0.31 W} \frac{100 - A - W}{100} \frac{V_L p}{(p + p_l)^2} \right) \frac{\partial p}{\partial t} - \frac{k M_c}{\mu} \nabla (p \nabla p) = 0.
\]

(12)

Eq. (2) describes the change in cohesion in the strain-softening model; Eqs. (4)–(6) describe the permeability evolution in the coal surrounding the borehole after hydraulic flushing; and Eq. (12) expresses the gas flow in the gas extraction process. By solving these equations, we can obtain the permeability evolution and the gas flow characteristics in the coal surrounding the borehole after hydraulic flushing.

### 3.2. Geometric model and parameter setting

To solve the above governing equations, the solid mechanics module and the PDE module in the finite-element computer program COMSOL Multiphysics are used in this paper. To simplify the calculation, a two-dimensional model is established based on the plane strain assumption, as shown in Fig. 6. The model is divided into the roof stratum, coal seam, and floor stratum with thicknesses of 5 m, 2.5 m, and 5 m, respectively. The only gas extraction borehole is located at the center of the coal seam. The boundary and initial conditions for the solid deformation model and gas flow model are separately set. For the solid deformation model, the right and bottom sides are set as roller boundaries, and the top and left sides are set as stress boundaries with a normal stress of 10.05 MPa. For the gas flow model, a constant pressure of 76 kPa (25 kPa less than the normal atmospheric pressure) is applied to the wall of the borehole, and no flow conditions are applied to the other boundaries. The parameters in the simulation are listed in Table 1. Most parameters are selected from the tested results in the laboratory or the field; the cleat volume compressibility and jump coefficient of permeability are cited from previously published references (Guo et al., 2014; Zhao et al., 1999). Furthermore, a monitoring line (x: 10–16 m; y: 6.25 m) is set in the coal surrounding the borehole in the simulation process.

### 3.3. Results and discussion

According to Gao et al. (2015) and Kong et al. (2016), the larger the RB, the better the gas extraction effect. However, considering that the support of a coal roadway becomes difficult if the RB is too...
large, the maximum RB is currently set at 0.4 m for the Xinjing coal mine. As a result, the following RBs have been selected in this paper to study the permeability-increasing mechanism of the ISBH technology and the gas flow characteristics of the hydraulic flushing boreholes: 0.045 m (the radius of ordinary in-seam borehole), 0.1 m, 0.2 m, 0.3 m, 0.4 m, 0.5 m, 0.6 m, and 0.7 m.

3.3.1. Permeability-increasing mechanism

We consider a borehole with a radius of 0.4 m as an example. After the borehole construction, the equivalent plastic shear strain, volumetric stress and permeability ratio cloud charts in the coal surrounding the borehole are shown in Fig. 7. According to the plane strain assumption, $\sigma_2$ can be considered a constant, and only $\sigma_1$ and $\sigma_3$ are calculated in the volumetric stress equation.

After the borehole construction, the equivalent plastic shear strain is greater than 0 in the coal surrounding the borehole (Fig. 7b), which indicates that the plastic failure occurs in the coal mass. Simultaneously, the volumetric stress dramatically decreases (Fig. 7c). With the failure of the coal mass and the decrease in volumetric stress, the permeability significantly increases (Fig. 7d).

In the areas closer to the borehole, the plastic failure is more severe, and the residual volumetric stress is lower, which causes higher permeability.

The monitoring results of the equivalent plastic shear strain, volumetric stress and permeability ratio in the coal surrounding the borehole are shown in Fig. 8. The equivalent plastic shear strain is 0 and 0.01 (Table 1) at the beginning of the strain-softening stage and residual stage, respectively. Thus, the coal surrounding the borehole is divided into a plastic residual zone, a plastic softening zone, and an elastic zone. As shown in Fig. 8a and b, the thickness of

Table 1

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<th>Parameter type</th>
<th>Parameter</th>
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Fig. 7. Equivalent plastic shear strain, volumetric stress and permeability ratio cloud charts in the coal surrounding the borehole: (a) permeability-increasing zone; (b) equivalent plastic shear strain; (c) volumetric stress; and (d) permeability ratio.
the plastic residual zone is 0.41 m. In this zone, the equivalent plastic shear strain is greater than 0.01, which indicates that serious plastic failure occurs in the coal mass. Meanwhile, the volumetric stress decreases below 16.4 MPa. Under the comprehensive action of the equivalent plastic shear strain and volumetric stress, the permeability increases up to 44 times the initial value.

Moreover, a 0.13-m-thick plastic softening zone appears near the plastic residual zone, as shown in Fig. 8a and c. In the plastic softening zone, the equivalent plastic shear strain is 0.01, which implies that the plastic failure in the coal mass is relative weak. At the boundary between the plastic residual zone and the plastic softening zone, the volumetric stress is approximately 16.4 MPa. However, at the boundary between the plastic softening zone and the elastic zone, the volumetric stress increases to its initial value (20.1 MPa). In this zone, the permeability increases up to 144 times the initial value, which is smaller than that in the plastic residual zone. In the elastic zone, the equivalent plastic shear strain is 0, which indicates that the coal mass does not fail. Simultaneously, the volumetric stress remains unchanged, which is consistent with the previous study results (Brady and Brown, 2006; Cheng, 2012; Sheng et al., 2007; Zhang, 2015). Thus, the permeability remains unchanged in the elastic zone, as shown in Fig. 8a and c.

In summary, the permeability increases in the plastic zone and remains constant in the elastic zone. Therefore, the coal surrounding the borehole can be divided into a permeability-increasing zone and an initial permeability zone, as shown in Fig. 9a. However, Gao et al. (2015) deemed that the volumetric stress increased near the boundary between the plastic zone and the elastic zone, which could result in a permeability-decreasing zone (Fig. 9b). As mentioned, the constant volumetric stress remains unchanged in the elastic zone and has been confirmed by many experts and scholars (Brady and Brown, 2006; Cheng, 2012; Sheng et al., 2007; Zhang, 2015). Hence, the research results of Gao et al. (2015) are incorrect.

3.3.2. The effect of RB on permeability evolution

In this chapter, the effect of RB on permeability evolution is analyzed. At different RBs, the evolution of the equivalent plastic shear strain, volumetric stress and permeability ratio in the coal surrounding the borehole are shown in Fig. 8b.

As shown in Fig. 10a and b, with the increase in RB, the scopes of the plastic zone and the volumetric-decreasing zone gradually increase. However, at the wall of the borehole, the equivalent plastic shear strain is constant at 0.46 (Fig. 10a), and the volumetric stress is constant at 2.14 MPa (Fig. 10b). To verify the simulated volumetric stress at the wall of the borehole, the theoretical solution of the stress is used. According to Wang et al. (2012) and Yao et al. (2010), the calculation formulas of the radial stress and tangential stress in the plastic zone around the borehole based on the limit-equilibrium assumption are expressed as follows:

$$
\sigma_{lp} = \frac{q}{\varepsilon - 1} \left( \frac{r}{R_0} \right)^{\varepsilon - 1} - 1
$$

$$
\sigma_{tp} = \frac{q}{\varepsilon - 1} \left( \frac{r}{R_0} \right)^{\varepsilon - 1} - 1
$$

where $\sigma_{lp}$ is the radial stress, $\sigma_{tp}$ is the tangential stress, $q = 2c/\sqrt{\varepsilon}$, $\varepsilon = \frac{1 - \sin \phi}{1 + \sin \phi}$, $r$ is the distance from the center of the borehole, and $R_0$ is the radius of the borehole.

If we substitute a residual cohesion of 0.6 MPa and a friction angle of 32° of the coal mass (Table 1) into Eq. (13), the volumetric stress at the wall of the borehole ($r = R_0$) is constant at 2.16 MPa. The calculation result is consistent with the simulation result.

Moreover, the permeability ratio exhibits the same trend as the equivalent shear strain and the volumetric stress (Fig. 10c). At the wall of the borehole, the maximum permeability (380 times the initial value) is also a constant. However, as shown in Fig. 10d, the radius of the permeability-increasing zone linearly increases with

Fig. 8. Monitoring results of the equivalent plastic shear strain, volumetric stress and permeability ratio: (a) general drawing; (b) the boundary between the plastic residual zone and the plastic softening zone; and (c) the boundary between the plastic softening zone and the elastic zone.
increasing RB:

\[ R_i = 2.30R_0, \]

where \( R_i \) is the radius of the permeability-increasing zone.

As RB increases from 0.045 m to 0.7 m, the radius of the permeability-increasing zone increases from 0.11 m to 1.61 m, which indicates that hydraulic flushing can improve the permeability of the coal seam.

3.3.3. Gas flow characteristics of the hydraulic flushing boreholes

According to the above permeability simulation results, the gas extraction at different RBs can be simulated, as shown in Fig. 11.

Considering a borehole with a radius of 0.4 m as an example, the gas flow characteristics are different in different zones, as shown in Fig. 11a and b. In the plastic residual zone and plastic softening zone, the gas pressure rapidly decreases, which indicates that gas extraction is relatively easy in these two zones. After 10 days of gas extraction, the gas pressure in the plastic residual zone decreases to

Fig. 9. Comparison of research results: (a) results of the paper and (b) Gao’s results (Gao et al., 2015).

Fig. 10. The simulation results at different RBs: (a) equivalent plastic shear strain; (b) volumetric stress; (c) permeability ratio; and (d) radius of the permeability-increasing zone.
nearly the gas extraction pressure (76 kPa). However, the gas pressure slowly decreases in the elastic zone, which suggests that the gas extraction is difficult. Different gas extraction conditions between the plastic softening zone and the elastic zone result in a large gas pressure gradient near the boundary between these two zones. The gas flow characteristics are consistent with the permeability evolution in the coal surrounding the borehole.

After 20 days of gas extraction, the gas pressure distributions in the coal surrounding the borehole at different RBs are shown in Fig. 11c. This figure indicates that a larger RB corresponds to a more drastic decrease in gas pressure. In China, a gas pressure of 0.74 MPa is the criterion specified by the government to evaluate the gas extraction effect, and the region where the gas pressure is less than 0.74 MPa is defined as the influence zone of a borehole. Therefore, the influence radii of different RBs can be obtained, as shown in Fig. 11d. In Fig. 11d, the influence radius increases from 0.28 m to 2.10 m when the RB increases from 0.045 m to 0.7 m, which indicates that hydraulic flushing can significantly improve the gas extraction effect of in-seam boreholes. The relationship between the influence radii and the RBs can be well fitted to a polynomial model, which is consistent with the conclusion of Kong et al. (2016).

4. Gas extraction scheme design and field application

4.1. Design procedures

The excavation speed of the S5 intake airflow roadway can be significantly increased by decreasing the gas extraction time to less than 20 days in each gas extraction cycle. To ensure that the coal and gas outburst risk could be successfully eliminated in each section after 20 days of gas extraction, the gas extraction scheme should be well designed.

As mentioned, the maximum RB is currently set at 0.4 m for the Xinjing coal mine; specifically, the RB in section I is 0.4 m (Fig. 4b). Therefore, the design procedures are as follows: (1) select the optimal MBS \( d_{\text{max}} \) (Fig. 4b) in section I using an RB of 0.4 m; (2) design the boreholes according to the MBS in step 1; and (3) select the optimal RBs for sections II and III. After step 2, the BSs in sections II and III are obtained, and the optimal RBs in these two sections can be designed. For safety, the RB should be designed according to the MBS in either zone.

4.2. Gas extraction scheme design

The gas extraction scheme is also designed using a numerical simulation method. Considering that multiple boreholes may affect one another during the gas extraction process (Gao et al., 2016), three gas extraction boreholes are built in the geometric model, as shown in Fig. 12. The governing equations, boundary conditions, and parameters are identical to those in Fig. 6. In the simulation process, a gas pressure monitoring line \((x: 0 \text{ to } 20 \text{ m}, y: 7.5 \text{ m})\) is set at the upper boundary of the coal seam.

4.2.1. Selection of the optimal MBS in section I

As shown in Fig. 11d, the influence radius of a single borehole with a radius of 0.4 m is approximately 1.4 m at 20 days. In general, the MBS in section I would be set to 2.8 m, which is twice the influence radius of a single borehole (Kong et al., 2016). However, to account for the interactions among multiple boreholes, five BSs are used in the simulation process to select the optimal MBS in section I: 2.8 m, 3.2 m, 3.6 m, 4.0 m, and 4.4 m. The simulation results are shown in Fig. 13.
As shown in Fig. 13, the gas pressure significantly decreases in the coal surrounding the borehole during the gas extraction process. A smaller BS results in a more significant decrease in gas pressure and a better gas extraction effect. Moreover, when we consider the interactions among multiple boreholes in the gas extraction process, the gas pressure between two adjacent boreholes can be decreased below 0.45 MPa for a BS of 2.8 m (Fig. 13b). The residual gas pressure is markedly lower than 0.74 MPa, which indicates that the interactions among multiple boreholes can significantly affect the gas extraction (Gao et al., 2016). The residual gas pressure between two adjacent boreholes can also be decreased below 0.70 MPa for a BS of 4.0 m after 20 days of gas extraction (Fig. 13b). Thus, 4.0 m is an appropriate selection for the optimal MBS in section I.

### 4.2.2. Borehole design

If the MBS is set to 4.0 m in section I, 17 boreholes are required in each gas extraction cycle, as shown in Fig. 14. Under these circumstances, the MBS in section II is approximately 3.1 m, while the MBS in section III is approximately 2.4 m.

### 4.2.3. Selection of the optimal RB in section II

As shown in Fig. 14, the MBS is approximately 3.1 m in section II. For a BS of 3.1 m, the following RBs are selected to study the optimal RB in section II: 0.15 m, 0.20 m, 0.25 m, 0.30 m, and 0.35 m. According to the gas extraction simulation results in Fig. 15, the residual gas pressure between two adjacent boreholes can be decreased below 0.71 MPa for an RB of 0.25 m, which indicates that 0.25 m is an appropriate selection for the optimal RB in section II.

### 4.2.4. Selection of the optimal RB in section III

Fig. 14 shows that the MBS is approximately 2.4 m in section III. For a BS of 2.4 m, the following RBs are selected to study the optimal RB in section III: 0.045 m, 0.10 m, 0.15 m, 0.20 m, and 0.25 m. According to the gas extraction simulation results in Fig. 16, the residual gas pressure between two adjacent boreholes can be decreased below 0.70 MPa for an RB of 0.15 m, which suggests that 0.15 m is an appropriate selection for the optimal RB in section III.

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**Fig. 12.** Geometric model for gas extraction of multiple boreholes.

**Fig. 13.** The gas extraction simulation results in section I: (a) gas pressure cloud charts; (a-i) 2.8 m; (a-ii) 3.2 m; (a-iii) 3.6 m; (a-iv) 4.0 m; (a-v) 4.4 m; and (b) gas pressure monitoring results.

**Fig. 14.** Borehole design chart.
4.3. Field application and model verification

4.3.1. Main devices

Based on the water-jet technique, a system (Fig. 17) for constructing large diameter in-seam borehole has been developed, and this system includes the following parts: (1) a crawler-type water tank, which provides high-pressure water for the system; (2) a drilling rig, which provides power for drilling; (3) a drill bit, which is used for drilling and flushing; (4) high-pressure water transport devices, including a high-pressure water tube, a high-pressure-resistant sealing rotator, and a high-pressure-resistant sealing drill pipe, which are used to transport the high-pressure water in the system; and (5) a coal-water-gas separation instrument, which is fixed between the drill pipe and the wall of the borehole to collect the coal, water, and gas that is discharged in the hydraulic flushing process.

4.3.2. ISBHF gas extraction procedures

During ISBHF gas extraction, the construction procedures for one borehole are as follows:

1) Drilling an ordinary in-seam borehole: open the drilling nozzle of the drill bit, and drill the in-seam borehole to the design length.
2) Hydraulic flushing: after drilling an ordinary in-seam borehole, the high-pressure-resistant sealing drill pipe backs out rotationally at a constant speed. During this process, open the flushing nozzle, and flush the coal surrounding the borehole with the high-pressure water jet. The high-pressure water jet breaks up the surrounding coal, which is discharged through the borehole along with the water. The RB could be controlled by the mass of the discharged coal (MDC) and the flushing time. The relationship between the MDC per meter of borehole with the RB could be expressed as follows:

\[ m_c = \pi \rho_1 \left( r_2^2 - r_1^2 \right), \]  \hspace{1cm} (15)

where \( m_c \) is the MDC per meter of the borehole (t/m), \( \rho_1 \) is the density of the wet coal (1.4 t/m³), \( r_2 \) is the RB after hydraulic flushing (m), and \( r_1 \) is the RB before hydraulic flushing (0.045 m).

The field construction experience at the Xinjing coal mine indicates that the average discharging velocity of the broken coal is approximately 0.036 t/min during the flushing process. Therefore, the control indexes of RB could be obtained, as shown in Table 2.

3) Gas extraction: after hydraulic flushing, seal the borehole, and extract the pressure-relief gas.

4.3.3. Residual gas contents and model validation

According to the designed gas extraction scheme, devices, and construction procedures, the ISBHF gas extraction technology was implemented in the S5 intake airflow roadway. The construction of 17 boreholes took 15 days, and more than 320 t of coal was discharged. After 20 days of gas extraction, three gas content monitoring boreholes were drilled in the coal seam near the roof to determine the maximum residual gas contents in each section, as shown in Fig. 18.
80 m before the heading face. In sections II and III, the measuring points were arranged 37 m and 57 m before the heading face, respectively, to avoid the effect of the adjacent section. The residual gas contents were determined using the direct method (Wang et al., 2015), and the results are shown in Table 3.

According to Wang et al. (2015), the relationship between the

Table 2
The control indexes of RB during the flushing process.

<table>
<thead>
<tr>
<th>Section</th>
<th>RB after hydraulic flushing (m)</th>
<th>MDC per meter of borehole (t/m)</th>
<th>Flushing time per meter of borehole (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>0.40</td>
<td>0.70</td>
<td>20</td>
</tr>
<tr>
<td>II</td>
<td>0.25</td>
<td>0.27</td>
<td>7.5</td>
</tr>
<tr>
<td>III</td>
<td>0.15</td>
<td>0.09</td>
<td>2.5</td>
</tr>
</tbody>
</table>

Fig. 17. Main devices: (a) crawler-type water tank; (b) drilling rig; (c) drill bit; (d) high-pressure-resistant sealing rotator; (e) high-pressure-resistant sealing drill pipe; and (f) coal-water-gas separation instrument.

Fig. 18. The arrangement of the monitoring boreholes and measuring points.
gas content and gas pressure could be expressed as follows:

\[ X = \frac{V p T_0}{(T p_0 \psi)} + \frac{V L p e^{n(\psi - 1)}}{p + p_L e^{(0.31W - 1)}} \frac{100 - A - W}{100} \]  

(16)

where \( X \) is the gas content under standard conditions \((\text{m}^3/\text{t})\), \( V \) is the pore volume per unit mass \((0.046 \text{ m}^3/\text{t} \text{K}) \) in Xinjing coalmine, \( p \) is the gas pressure (MPa), \( T_0 \) is the temperature at standard conditions \((273.2 \text{ K})\), \( T \) is the gas temperature \((293.2 \text{ K} \text{K}) \) in Xinjing coalmine, \( p_0 \) is the pressure at standard conditions \((0.101 \text{ MPa})\), \( \psi \) is the compressibility factor for methane \((\psi = 1)\), \( n \) is a coefficient, \( n = 0.02 / (0.993 + 0.07p) \), \( t_0 \) is the lab temperature \((\text{K})\), and \( t \) is the coal temperature \((\text{K})\).

We assume that the lab temperature \((t_0)\) is equal to the coal temperature \((t)\) and substitute the related parameter values in Table 1 into Eq. (16); then, the residual gas contents are converted to residual gas pressures, as shown in Table 3. In Table 3, the maximum residual gas pressures in sections I-III are 0.65 MPa, 0.72 MPa, and 0.69 MPa, respectively. These values are lower than 0.74 MPa, indicating that the coal and gas outburst risk is successfully eliminated in each section.

Moreover, in Table 3, the average residual gas pressures at the measuring points in each section (Fig. 18) are 0.60 MPa, 0.64 MPa, and 0.62 MPa, respectively. According to the simulation results in chapter 4.2, the residual gas pressures at these measuring points should be 0.70 MPa, 0.71 MPa, and 0.70 MPa. The field test results are consistent with the simulation results (Fig. 19) with an average relative error of 13.4%. Thus, our model is valid for analyzing the gas extraction from boreholes after hydraulic flushing. The small error may be caused by the gas flow in the hydraulic flushing process, which is ignored in the simulation process for simplicity and can result in a larger residual gas pressure.

### 4.3.4. Comparisons of the gas extraction effect

Two gas extraction cycles in the S5 intake airflow roadway, using the ordinary and the ISBHF gas extraction technologies, are selected to compare the gas extraction effect. The geological and gas conditions in these two cycles are approximately identical, and the comparison results are shown in Fig. 20.

The gas extraction data of these two gas extraction cycles over the same gas extraction time are compared in Fig. 20a. This figure shows that the gas extraction concentration in the ISBHF gas extraction process is 30% (on average), and the gas extraction flow is 1.0 m³/min (on average). These values are 10 times and 6 times greater than the values achieved with the ordinary technology, respectively. After the gas extraction in each cycle, the roadway is allowed to be excavated forward for 60 m (leaving 20 m for next cycle, as shown in Fig. 2). During the excavation process of the coal roadway, the risk of coal and gas outburst in the coal roadway is evaluated using the gas desorption index of drilling cuttings \((K_i)\) and the quantity of the drilling cuttings \((S)\). By considering that the gas in the first 20 m of each gas extraction cycle has been extracted in the previous cycle (Fig. 2), only the outburst forecast predictors determined between 20 and 60 m of these two cycles are used to compare the gas extraction effect. As shown in Fig. 20b and c, during the coal roadway excavation process using the ordinary gas extraction technology, these two parameters increase gradually due to the increase in BS (Fig. 4a). At 50 m before the heading face, the two parameters exceed the critical values, which indicates that the gas extraction is unqualified. However, this phenomenon is successfully eliminated by using the ISBHF gas extraction technology because the gas extraction scope is divided into different sections and because greater RBs are designed in the sections with greater BSs.

As shown in Fig. 20d, using the ISBHF gas extraction technology at the Xinjing coal mine decreases the number of gas extraction boreholes in each gas extraction cycle from 34 to 17 (a decrease of 50%) and decreases the gas extraction time from 45 days to 20 days (a decrease of 56%). In addition, this technology increases the average monthly excavation length of the coal roadway from 20 m to 40 m (an increase of 100%), which indicates that the ISBHF gas extraction technology significantly improves the gas extraction efficiency and the excavation speed of the coal roadway in the soft and low-permeability coal seams.

### 5. Conclusions

Considering the difficulty of gas extraction from the heading face in the soft and low-permeability coal seams, a novel ISBHF gas extraction technology is proposed in this paper. The primary conclusions are as follows:

1) After hydraulic flushing, there forms a plastic residual zone, a plastic softening zone and an elastic zone in the coal
surrounding the borehole. With the failing of the coal mass and the decreasing of the volumetric stress, the permeability increases hundreds of times in the plastic residual zone and dozens of times in the plastic softening zone. However, the permeability stays the same in the elastic zone because the coal mass does not fail and because the volumetric stress does not change. As a result, the coal surrounding the borehole is divided into a permeability-increasing zone and an initial permeability zone. Meanwhile, the radius of the permeability-increasing zone increases linearly with RB, which indicates that hydraulic flushing could improve the permeability of the coal seam.

2) In the gas extraction process, the gas pressure decreases rapidly in the plastic zone but decreases slowly in the elastic zone. In addition, the greater the RB, the more drastically the gas pressure decreases in the coal surrounding the borehole; therefore, the influence radius of a single borehole increases with increasing RB for the same gas extraction time. These results indicate that hydraulic flushing could increase the gas extraction efficiency of the boreholes.

3) Considering the divergent characteristics of boreholes in the heading face and the interactions among multiple boreholes in the gas extraction process, a reasonable gas extraction scheme is designed and implemented at the Xinjing coal mine. The field test results show good agreement with the simulation results, validating our model. In addition, after using this new technology, the number of gas extraction boreholes in the heading face decreased by 50%. Conversely, the gas extraction-based concentration and flow increased by 10 and 6 times, respectively. Moreover, the outburst forecast predictors ($K_1$ and $S$) significantly decrease, and the monthly excavation length of the coal roadway increases by 100%. These results indicate that this new technology is a promising method for achieving efficient gas extraction and rapid excavation in the heading face of soft and low-permeability coal seams.

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