INTRODUCTION

Coalbed methane (CBM), also known as coal seam gas (CSG), is a substitute for conventional fuel, formed in both low-rank and high-rank coalbeds. According to statistics, the CBM reserves with a depth above 2000 m in China are around 36.8 × 10^12 m³, ranking the third largest in the world after Russia and Canada. As much more attention paid to industrial safety and environment protection, approximately 20,000 CBM wells were drilled throughout the past decades, and the production of CBM has dramatically increased to 7.02 × 10^9 m³ with an growth rate of 8.2% in 2017. Unfortunately, only 1/4 of these wells have achieved the commercial gas production of over 1000 m³/d due to the insufficient resource intensity and limitations of reservoir stimulation technologies. Gas recovery from deep underground coal mine seems a promising solution for the energy crisis. However, as most of coalfields in China are characterized by low permeability (K ≤ 0.005 mD), small firmness (f ≤ 1), strong adsorption, and high gas pressure (P ≥ 0.74 MPa), some enhanced coalbed methane recovery (ECBM) techniques are not applicable.
Currently, waterjet technique is widely used for material cutting in civil construction, \(^{15}\) cleaning operations, \(^{16}\) hydraulic mining, and petroleum drilling, \(^{17,18}\) especially in natural gas exploration. \(^{19}\) Reservoir stimulation using waterjet, such as hydraulic flushing/slotting, has been identified as an effective technique to cut slots and release pressure, by enhancing the gas production. Gao et al. \(^{20}\) analyzed the permeability variation in coalbed after waterjet operation and divided the surrounding coal near borehole into a permeability-increasing zone, a permeability decreasing zone, and an initial permeability zone, respectively. Wang et al. \(^{21}\) simulated the fracture evolution of coalbed during hydraulic flushing by RFPA2D-Flow and also found that the regularity of permeability change is consistent with the change in principal stress. There is an obvious drop in both stress and gas pressure near the borehole; further, the permeability coalbed is substantially improved following hydraulic flushing and slotting. Zou et al. \(^{22}\) investigated the property of gas adsorption by waterjet treatment. It is revealed the adsorption constant presents a rising tendency, and the adsorption constant \(b\) has an opposite variation tendency with the increase in borehole distance. Tang et al. \(^{23}\) discussed how the water invasion interacts with adsorbed gas in molded coal under elevated pressures using a custom-designed instrument. Lu et al. \(^{24,25}\) considered the nozzle geometrical parameters and water pressure are crucial for the penetration depth, and a significant improvement of gas recovery efficiency has been achieved using waterjet. Kong et al. \(^{26}\) discussed the coupled effect of multifactors on the effective influence radius of waterjet and found the effective influence radius increased with borehole radius and initial permeability, but decreased with the initial gas pressure. Shen et al. \(^{27}\) conducted an electromagnetic radiation (EMR) experiment to evaluate the waterjet effect on gas drainage in Liangbei coal mine. Subsequently, Cheng et al. \(^{28}\) applied hydraulic flushing technique into in-seam borehole gas extraction, which results in a 50% decrease in the number of drainage boreholes in the heading face. Lin et al. \(^{29}\) developed a enhanced coalbed methane recovery (ECBM) technique based on the integration of hydraulic slotting and hydraulic fracturing.

These studies provide reliable support for the waterjet application in underground gas recovery. However, submerged jet conditions are inevitable in the field. For instance, in downward holes, since it is difficult to drain off water in time due to gravity, the whole process of jet is completely submerged. Additionally, in horizontal and even upward holes, water may be stored up in the bottom of erosion pit or coal fractures, by forming a local submerged jet. The axial cutting capacity of jet would be largely weakened by the effects of entrainment and turbulence under submerged conditions, \(^{30,31}\) and thus, the later gas production directly shrunk. More seriously, some fade zones of gas drainage are indeed caused by the unreasonable layout of boreholes, which leaves a hidden safety danger. \(^{32}\) Hence, the investigation into cutting efficiency under different submerged conditions has a great significance for the efficient utilization of waterjet in reservoir stimulation.

Gimaltdinov and Kildibaeva \(^{33}\) developed an integral Lagrangian control volume method for calculating the submerged jet parameters under the stable hydrate conditions. Liao et al. \(^{34}\) adopted a digital controlled super-high-pressure jet cutting machine to investigate the optimal standoff distance and jet angle of rock cutting under submerged conditions. Ezddin et al. \(^{35,36}\) conducted experimental study on the influence of geometrical parameters on the cavitation erosion process by exposing the surfaces of copper samples to high-speed submerged jets with the assist of digital camera. Tian et al. \(^{37}\) combined acoustic emission (AE) sensing with underwater sound recording techniques for monitoring the sediment drilling process by submerged waterjet. It shows AE signal frequencies from fluid dynamics, and rock failures are in different ranges: The rock failure frequencies are within a higher range of 100-200 kHz, while the jet frequencies are below 50 kHz, and there is a linear relationship between the AE energy and the cutting depth, irrespective of rock type. Besides, the spectra of turbulent jet temperature pulsations at 1-40 Hz frequencies have been experimentally studied via high-speed thermography of the water layer boundary. \(^{38}\) Due to the limited experimental conditions, it is still extremely difficult to observe the breaking process and the stress evolution of coal in milliseconds. So many scholars conducted numerical simulation work on the submerged jet cutting process. For the prediction of heat losses from the hot jet to the cold aqueous environment, a numerical model based on the commercial computational fluid dynamics (CFD) tool was established to determine penetration lengths of submerged supercritical waterjets near critical pressures. \(^{39}\) Then, the finite element method of smooth particle hydrodynamics (SPH-FEM) \(^{40-42}\) and Arbitrary Lagrange-Euler (ALE) algorithms \(^{43-46}\) were widely employed to analyze the microscopic damage of rock induced by submerged waterjet and the evolution of stress waves in rock. Besides, Li et al. \(^{37}\) employed a fluid-solid coupled model in Fluent to reveal the effects of thermal stresses in continuous submerged waterjet during rock breaking.

To the authors’ knowledge, most previous studies have focused on the process of rock cutting by submerged waterjet. Little insight has been gained about optimizing jet parameters during coalbed stimulation. Compared with rock, the coalbed containing mass gas has a self-outburst property, which affects the overall cutting performance. This paper proposes a fluid-solid coupled model of coal containing gas breaking by waterjet via ALE algorithm in LS-DYNA software. The dynamic evolution of coal damage and the cutting performance under different conditions, including jet pattern, jet velocity, nozzle diameter, and the initial standoff distance, are investigated by tracing the number of failure elements and the stress distribution. Afterward, a coupled model of gas flow is built to analyze
interactions of the coal cutting amount and the effective radius of gas recovery at different prerecovery time with COMSOL software. On the basis of optimal drainage parameters gained by numerical simulations, the feasibility of using submerged waterjet to enhance underground gas recovery production is eventually verified in Liulong coal mine, Guizhou Prov., China.

2 | COAL CUTTING PERFORMANCE BY WATERJET

Coal cutting by waterjet produces a large transient dynamic load, a large strain, high strain rates, and high pressure, and its mechanism is quite complex, involving solid-liquid coupled interaction of coal, water, and air. Laboratory tests can not adequately detect the instantaneous stress state and the evolution of coal cutting performance. Thus, the ALE method, which satisfied the above working conditions, was performed to establish coupled models of coal containing gas cutting by waterjet under submerged/nonsubmerged conditions by using LS-DYNA program.

2.1 | Numerical modeling

For the symmetric problem, a 1/4 model of coal considered as a continuum media, was meshed with axisymmetric elements to improve the calculation rate. The free mesh method was selected to divide the jet, water and gas area, meanwhile the mapping mesh used for the coal, as shown in Figure 1. The model is 50 × 50 × 100 cm in dimension. The Johnson-Holmquist-Concrete (J-H-C) damage model was adopted, which is suitable for simulating the large strain behavior of coal containing gas impacted by waterjet. The features of J-H-C model cover isotropic constitutive equations, a plastic yield surface with a smooth cap, three yield surfaces of stress invariant with the prepeak hardening translation, and the strain softening effect. The model assumes the following: (a) the waterjet is regarded as a continuous homogeneous fluid; (b) the coal is assumed to be continuous, uniform and isotropic; and (c) the cavitation effect induced by waterjet is neglected. Based on the geological drilling background in Liulong coal mine, to coincide with the coal cutting experiment, the material parameters in the J-H-C model were listed in Table 1. Moreover, the confining pressure of 5.6 MPa was loaded on the top boundary as in-situ stress and the gas pressure in coal is 1 MPa. Full constraints and non-reflective boundary conditions are applied to the coal bottom to simulate the infinite space area.

2.2 | Governing equations in ALE framework

The continuity equation of flow in the model is described as follows:

$$-\frac{\partial \rho}{\partial t} = \rho \frac{\partial v_i}{\partial x_i} + \nabla \cdot w$$

where $\rho$ is the density of liquid medium, kg/m$^3$; $x_i$ and $x_j$ are the displacement components in the direction of $i$ and $j$, respectively; $m$; $v_j$ and $v_i$ are the velocity components, m/s; and $t$ is time, seconds.

The momentum equation of jet is shown as follows:

$$v \frac{\partial v_j}{\partial t} = \sigma_{ij,j} + \rho b_i - \rho w_i \frac{\partial v_j}{\partial x_j}$$

where $\sigma_{ij,j}$ is the partial derivative of stress tensor; $b_i$ is the body force, N; and $w_i$ and $w_j$ are the components of relative velocity, m/s.

The energy equation of jet is shown as follows.

$$\rho \frac{\partial E}{\partial t} = \sigma_{ij,v_{ij}} + \rho b_i v_i - \rho w_i \frac{\partial E}{\partial x_j}$$

where $E$ is the inner energy density of liquid, J/m$^3$.

The Gruneisen state equation, given in Equation 4, is adopted to characterize the flow of water and gas because of the pressure response:

$$P = \frac{\rho_0 C^2 \mu \left[ 1 + (1 - \frac{\nu}{2})\mu - \frac{a}{2} \mu^2 \right] }{\left[ 1 - (S_1 - 1)\mu - S_2 \mu_1 + S_3 \mu_2 \right] \left[ (1 + \mu)^2 \right] } + \gamma_0 + a\mu \epsilon$$

where $P$ is the medium pressure, MPa; $\rho_0$ is the initial density, kg/m$^3$; $S_1$, $S_2$, and $S_3$ are fitting coefficients; $\gamma_0$ is the Gruneisen coefficient; $\alpha$ is Poisson’s ratio; $\mu$ is the viscosity coefficient; and $C$ is the interception of the relation between the velocity of shock wave $\mu_s$ and the particle velocity $\mu_p$. The relation between $\mu_s$ and $\mu_p$ is given as follows.

$$\mu_s = C + S_4 \mu_p + S_5 \left( \frac{\mu_p}{\mu_s} \right)^2 \mu_p + S_3 \left( \frac{\mu_p}{\mu_s} \right)^3 \mu_p$$

For coal cutting, the normalized equivalent stress is described as follow in J-H-C model.

$$\sigma^* = \left[ A(1-D) + BP^{nN} \right] \cdot \left( 1 + C \ln \epsilon^* \right)$$

where $\sigma^* = \frac{\sigma}{\epsilon^*}$, representing the ratio of the actual equivalent stress to the quasi-static compressive strength; $P^* = \frac{P}{\epsilon_0}$, representing the dimensionless pressure; $\epsilon^* = \frac{\epsilon}{\epsilon_0}$, representing the dimensionless strain rate; $\epsilon$ and $\epsilon_0$ are the true strain rate and the reference strain rate, respectively; $A$ is the dimensionless cohesion; $B$ is the normalized compressive coefficient; $C$ is coefficient of strain rate; $N$ is the exponent of stress hardening; and $D$ is the damage index, expressed as follows.
where $\Delta \varepsilon_p$ is the equivalent increment of plastic strain; $\Delta \mu_p$ is the equivalent increment of volume strain; $T^*$ is the maximum of hydrostatic tension; $D_1$ and $D_2$ are damage constants.

2.3 Results and discussion

2.3.1 The role of jet velocity

Essentially, waterjet is a hydraulic tool with flexible shapes to flush the geometry of workpiece by introducing the kinetic energy into workpiece surface, resulting in material removal. Thus, the characteristics of waterjet directly affect the process and the cutting performance. As a key factor, a higher jet velocity is believed to possess more impacting energy under the same conditions from an energetic viewpoint. The jet velocity from nozzle outlet depends on pumping pressure and water density, derived from the simplified Bernoulli’s equation as follows.

$$v = \sqrt{\frac{2P}{\rho}}$$  \hspace{1cm} (8)

where $v$ is the maximum jet velocity, m/s; $P$ is the pumping pressure neglecting the pipeline loss, MPa; and $\rho$ is water density, kg/m$^3$. When the standoff distance and nozzle diameter are settled, the velocity within jet range radially decreases away from the center line, which can be described as a bell-shaped profile. Further, the velocity distribution on each of jet cross section can be expressed by characteristic variables of velocity and scaled into the same mathematical model as shown in Equation 9, namely the self-similarity of jet velocity distribution.

$$\frac{v}{v_m} = \left[1 - \left(\frac{Y}{R}\right)^{1.5}\right]^2$$  \hspace{1cm} (9)

where $v$ is jet velocity at any point on the section, m/s; $v_m$ is jet velocity on the axis, m/s; $Y$ is the radial distance, m; and $R$ is the jet radius, m.

In order to investigate the roles of jet velocity on the performance of coal cutting both in submerged and nonsubmerged conditions, different jet velocities of 180-210 m/s were selected in the model. Besides, the jet angle consistently kept vertical to coal. The diameter of nozzle was 1.5 cm, and the standoff distance was set as 2 cm. By symmetry, the morphology of coal cutting under different jet velocities at 5000 $\mu$s was acquired as shown in Figure 3.

Figure 3 reveals the differences of erosion pit shape under two jet patterns. In submerged models, the erosion pit firstly presents a funnel shape and then columnarly extends.

| TABLE 1 Material parameters in the coupled model |
|-----------------------------------------------|
| Coal | $\rho$ (g/cm$^3$) | $G$ (GPa) | $A$ | $B$ | $C$ | $N$ | $F_1$ (GPa) | $T$ (GPa) | $E F_{min}$ | $S F_{max}$ |
|------|----------------|--------|-----|-----|-----|-----|-------------|---------|------------|------------|
| Coal | 1.4            | 2.48   | 0.79| 1.6 | 0.007| 0.61| 4.8e-4      | 4e-5    | 0.01       | 7          |
| $P_c$ (GPa) | $U_c$ | $P_L$ (GPa) | $U_L$ | $D_1$ | $D_2$ | $K_1$ (GPa) | $K_2$ (GPa) | $K_3$ (GPa) | $E$ |
| $-1.6e-4$ | 0.001 | 0.008 | 0.1 | 0.04| 1.0 | 0.85| $-1.71$     | 2.08    | 3.57       |
| Gas  | $\rho$ (g/cm$^3$) | $P_c$ (GPa) | $C$ | $S_1$ | $S_2$ | $S_3$ | $GAMA_0$ | $\alpha$ | $E$ |
| 1.29e-3 | $-8.5e-4$ | 0.0331 | 2.56 | 0 | 0 | 0 | 0 | 0 |
| Water | $\rho$ (g/cm$^3$) | $P_c$ (GPa) | $C$ | $S_1$ | $S_2$ | $S_3$ | $GAMA_0$ | $\alpha$ | $E$ |
| 1 | $-1e-5$ | 0.148 | 2.56 | 1.986 | 0.226 | 0.5 | 0 | 0 |
downward with the prolongation of jet time. Otherwise, that of nonsubmerged jet always holds linear. It may be because under submerged conditions, the secondary impact action inevitably exists in submerged jets by the turbulence effect. In the beginning, the high-speed shearing motion near jet boundary results in the water turbulence, accompanied by massive momentum transfer. As flowing downstream, the development and merging of vortices widen the turbulence range around jet. The momentum of water flowback affected by turbulence would be largely weakened, so that can not continually impact coal structure forward, making the shrinkage in the aperture of erosion hole. Thus, a funnel shape hole is formed. However in air, the momentum reduction of subsequent water flow is so faint that can effectively impact coal.

| Effective strain |
|------------------|
| **Submerged jet** |
| $v = 180 \text{ m/s}$ | $v = 190 \text{ m/s}$ | $v = 200 \text{ m/s}$ | $v = 210 \text{ m/s}$ |
| **Non-submerged jet** |
| $v = 180 \text{ m/s}$ | $v = 190 \text{ m/s}$ | $v = 200 \text{ m/s}$ | $v = 210 \text{ m/s}$ |

**FIGURE 2** Ground tests for the core impacting length of waterjet

**FIGURE 3** Effective strain distribution of two jet patterns by different velocities at 5000 μs
within a short standoff distance. The rebounding water evenly flows back from the wall after impacting coal elements, creating a narrow erosion pit along the jet direction.

Additionally, it is clearly concluded from Figure 4 that the penetration length increases with jet velocity. Under the submerged condition, waterjet can crush coal in a very short time and the cutting performance in initial stage of 0-100 μs is the highest. Then, the penetration length presents a step-by-step growth with time and eventually tends to stabilize and climbs no more at 5000 μs. It is mainly because in the initial stage, a short standoff distance has less influence on the cutting performance of jet with high energy. With the increase in penetration length, a massive momentum exchange occurs between the jet and surrounding water, by reducing the impacting energy. The jet continually crushes the radial coal under the water wedging action, thus causing the erosion section enlarged. For the continuous waterjet, the attenuation in the axial velocity is not notable within a short distance. Consequently, the penetration length increases with time and finally tends to stabilize when the momentum of jet is exhausted. On the nonsubmerged condition, the momentum exchange with air is so faint that waterjet can effectively impact coal in a straight line.

It can be seen directly from Figure 5 that both the penetration length and the number of eroded elements increase with the velocity of submerged jet. The final penetration lengths of submerged jet with different velocities of 180-210 m/s are 29, 34, 38, and 39 cm, respectively; and the total eroded numbers are 3285, 3550, 3997, and 4434, respectively. It is noticed that the increasing trend of penetration length gradually slows down when the jet velocity reaching 200 m/s, which indicates the cutting performance can be just improved substantially in a certain range of velocity, regarding the penetration length as
the effect evaluation. It should be because the energy losses along the path increase with the velocity as well under the coupled actions of turbulence and the water wedging. On the other hand, the cutting performance of nonsubmerged jet is almost unchanged with the velocity. Both the penetration length and the eroded number present a linear growth, which indicates the penetration length plays a leading role on the eroded element number of coal. The final penetration lengths of nonsubmerged jet are 74, 82, 87, and 94 cm, respectively, and the total eroded numbers are 2685, 2861, 3049, and 3191, respectively, whereas nozzle diameter determines the width of erosion pit formed by waterjet. Consequently, the cutting performance of nonsubmerged jet is largely superior to the submerged jet.

2.3.2 | The role of nozzle diameter

Based on the energetic viewpoint, the larger the diameter of nozzle, the more the impacting energy of waterjet under the same condition (see Equation 10). Previous studies have indicated that the cutting volume of rock shows a linear relation with nozzle diameter in the nonsubmerged condition.\(^\text{41,54,55}\) Whereas the waterjet technique is generally operated into the coal-uncovering section of borehole at a certain rotation and advancing speed, the penetration length becomes the evaluating indicator for coal cutting performance, instead of the cutting volume. Here, the submerged models with different nozzle diameters of 1–2.5 cm are established for the optimal cutting performance and less water waste. Besides, the jet angle consistently kept vertical to coal, and the jet velocity of 200 m/s and the standoff distance of 2 cm were set in each model.

\[ F = \frac{1}{4} \rho \pi D^2 v^2 \]  

(10)

where \( F \) is the impacting energy of waterjet, J; and \( D \) is nozzle diameter, m.

Figure 6 reveals the effect of nozzle diameter on the relative erosion shape of borehole in submerged condition. It can be seen that the penetration length almost increases with nozzle diameter increasing from 1 to 2.5 cm, but not substantially. Meanwhile, the erosion width of borehole was largely reamed with a bigger nozzle. Figure 7 shows the evolutions of penetration length and eroded elements with jet time. The penetration depth of coal presents a stair-step growth with impacting time, and the final depths by different nozzle diameters (1–2.5 cm) are 36, 38, 39, and 43 cm, respectively, at 5000 μs. While the eroded elements of coal approximately represent a linear increase with nozzle diameter, which is basically consistent with previous results, the ultimate numbers of eroded elements have a substantial growth, owing to the erosion width reamed. It means the increase in nozzle diameter in a certain range can not effectively improve the performance of coal cutting under submerged conditions, but results in the wastes of water and power.

The above results are mainly because that coal cutting was caused by many times of jet impacting action. After flushing coal in the axial direction, the rebounding waterjet remaining residual energy flows through borehole wall and continues to crush the surrounding damaged coal, hence reaming the hole aperture. Meanwhile, a layer of water cushion\(^\text{56}\) is formed between the jet and coal matrix, and the thickness of water cushion is closely related to the flowrate of jet. For a certain jet velocity, the bigger the nozzle diameter, the larger the flowrate. In this case, there is not enough time for water to diffuse, and thus, the thickness of water cushion gradually increased. It enormously weakens the impacting energy of the following jets and enhances the turbulence action, especially in a narrow erosion pit. Consequently, the increasing trend of penetration length is not obviously with nozzle diameter, but the reaming ability of rebounding jet is largely enhanced yet. Here, the penetration length of jet no longer dominates the ultimate number of eroded elements.

2.3.3 | The role of the initial standoff distance

The flow field structure of submerged waterjet\(^\text{31}\) is shown in Figure 8. The area between nozzle outlet and transition surface
is called the initial section of jet. In the initial section, there is a isovelocity core zone near the center axis, where the jet velocity at each point maintains the same as that of nozzle outlet. Beyond the core zone, the surrounding water will be entrained by jet, resulting in the jet boundary gradual widened along the path. When passing through the transition surface, the jet velocity along the axis begins to decrease gradually. The region behind the transition surface is called the basic section of jet, where the entrainment ability of jet is greatly enhanced, thus mixed with more water and forming a turbulent zone. Then, jets continue to flow forward till gradually loses the entrainment ability and fully integrate with the environmental media. This area is namely the jet dissipation section.

Under submerged conditions, the length of isovelocity core zone is much smaller than that of nonsubmerged jet. In the case of a large initial standoff distance, the coal cutting performance is hard to be effectively improved due to a fast attenuation of jet velocity in water, even if the initial velocity is enough high. Therefore, when using submerged waterjet impacting coalbed, it is necessary to shorten the initial standoff distance as possible, preferably within the isovelocity core zone, so as to ensure a higher coal cutting efficiency. To study the influence of the initial standoff distance on coal cutting performance, submerged waterjet models with different standoff distances of 1.5-3 cm were performed. Moreover, the jet angle consistently kept vertical to coal, and the jet velocity of 200 m/s and the nozzle diameter of 1.5 cm were set in each model.

As shown in Figure 9, it can be seen that the initial standoff distance does not change the shape of erosion pit too much under submerged conditions. Additionally, Figure 10 directly indicates both the penetration length and the cutting volume decrease with a larger standoff distance, presenting negative linear relations. This is mainly because the larger standoff distance, the longer exchange time between jet and surrounding water and the greater the impacting attenuation of jet, finally leading to a decline in the coal cutting performance. In the underground field, the initial distance of jet is usually not too far in boreholes due to a appropriate head-neck ratio of drilling tools, for example, a bit of 94 mm, the diameter of drill pipes of 50 mm, and the initial standoff distance of 22 mm. Thus, a larger reaming bit is unsuitable in waterjet operation.

3 | EFFECTIVE DRAINAGE RADIUS OF WATERJET

The effective drainage radius of waterjet generally refers to the minimum range, in which the drainage borehole can eliminate gas outburst risk along the radial direction by a certain prerecovery period after waterjet operation. It is mainly related to the coalbed permeability, the initial gas content, the amount of discharged coal, and the prerecovery period. According to Ten Provisions on Strengthening Gas Prevention and Control in Coal Mines promulgated by Chinese State Administration
of Coal Mine Safety, only when the gas pressure drops to 0.6 MPa and the gas content decreases to 6 m³/t can coalbed be considered to meet the standard of gas drainage. Currently, the methods of gas pressure drop and residual gas content are often applied to determine the effective drainage radius of borehole. Owing to a long period, difficult operation and low accuracy in underground gas pressure measurement, numerical results of pressure-drop method by using COMSOL Multiphysics were considered here.

### 3.1 Coupled model and governing equations

The coupled model of gas flow in coalbed was established to examine the effects of the amount of discharged coal by waterjet operation and the prerecovery period on the effective drainage radius via COMSOL Multiphysics, on the basis of geological conditions of No. 1075 drainage tunnel and gas occurrence of No. 7 coalbed, Liulong coal mine.

Since coal containing gas is a porous medium with complex structures, the following simplifications and assumptions must be introduced in the model: (a) The roof and the floor of coalbed with low permeability are considered as impermeable strata; (b) the coalbed is homogeneous and isotropic, submitted to Mohr-Coulomb failure criterion; (c) cross-measure boreholes are circular and vertically drilled into the coalbed; (d) gas diffusion meets the ideal gas equation, and gas flow obeys Darcy’s law.

Based on the mass conservation law, the continuity equation of gas flow is described as follows:

$$\nabla \cdot (\rho_g \mathbf{v}_g) + \frac{\partial w_p}{\partial t} = 0 \quad (11)$$

where $\rho_g$ is the gas density, kg/m³; $\mathbf{v}_g$ is the seepage velocity of gas, m/s; $w_p$ is the gas content in coal of per volume, kg/m³; $\nabla$ is the gas pressure gradient, MPa/m; and $t$ is time, s.

While the gas content in coal of per volume $w_p$ can be calculated as follows:

$$w_p = \beta \phi P + \frac{abcP}{1 + bp} \quad (12)$$

where $P$ is the gas pressure, MPa; $\beta$ is the compressibility coefficient of gas, kg/(m³·MPa); $a$, $b$ are adsorption constants; $c$ is the correction coefficient; and $\phi$ is the porosity of coal, %.

Further, the seepage velocity of gas $\mathbf{v}_g$ is written by correcting coal permeability with Klingberg coefficient.

$$V_g = -\frac{k}{\eta_g} \left( 1 + \frac{b_p}{p} \right) \nabla p \quad (13)$$

where $\eta_g$ is the dynamic viscosity coefficient of gas, Pa·s; $k$ is the permeability of coal, m²; and $b_p$ is the Klingberg coefficient.

Thus, the continuity equation of gas flow can be expressed as follows.

$$\left[ \frac{abc}{1 + bp} - \frac{ab^2cp}{(1 + bp)^2} + \beta \phi \right] \frac{\partial p}{\partial t} - \nabla \cdot \left[ \frac{k\beta}{\eta_g} \left( 1 + \frac{b_p}{p} \right) \nabla p^2 \right] = 0 \quad (14)$$

![FIGURE 9](image) Effective strain distribution of submerged jet with different standoff distances at 5000 μs

![FIGURE 10](image) Coal cutting performance of submerged jet with different standoff distances at 5000 μs
whereas the permeability of coalbed is not always a constant, varied with the stress distribution in rock strata, the bulk stress is used to describe the change in coal permeability as follows.

\[ k = k_a \exp \left( -b_s (\Delta \Theta) \right) \]  

(15)

where \( k_a \) is the absolute permeability of coalbed, \( m^2 \); \( \Theta \) is the effective bulk stress, MPa; and \( b_s \) is the influencing coefficient of bulk stress, MPa\(^{-1}\). On the other hand, the expansion or compression deformation would occur in coal matrix after jet cutting, also leading to the change in coal permeability. Thus, the Levine expansion model, related to effects of pore pressure and adsorption deformation, was adopted to express the deformation of coal matrix.\(^{60}\)

\[
\begin{align*}
\frac{\phi_i}{\phi} &= 1 + \frac{c_m}{3\phi} \left( p - p_0 \right) + \frac{\varepsilon_{LV}}{3\phi} \left( \frac{K}{M} - 1 \right) \left( \frac{p}{p_i^L + p} - \frac{p_0}{p_i^L + p_0} \right) \\
\frac{c_m}{M} &= K - \left( \frac{K}{M} + f - 1 \right) \beta \\
\frac{k_a}{k_0} &= \left( \frac{\phi_i}{\phi} \right)^3 \\
\end{align*}
\]  

(16)

where \( \phi_i \) is the effective porosity of coalbed, \%; \( \varepsilon_{LV} \) is the ultimate bulk deformation; \( p_i^L \) is the gas pressure of adsorption deformation, MPa; \( p_0 \) is the initial gas pressure in coalbed, MPa; \( c_m \) is the compressive coefficient, MPa\(^{-1}\); \( K \) is the bulk modulus of coal, GPa; \( k_0 \) is the initial permeability of coalbed, \( m^2 \); \( M \) is the first order Lame coefficient. \( M = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)} \) is Poisson’s ratio; and \( f \) is the correction coefficient, 0-1.

By solving the above simultaneous equations, the change in coal permeability can be expressed by the follow equation.

\[ k = k_0 \left[ 1 + \frac{1}{M \phi} \left( p - p_0 \right) + \frac{\varepsilon_{LV}}{3 \phi} \left( \frac{K}{M} - 1 \right) \left( \frac{p}{p_i^L + p} - \frac{p_0}{p_i^L + p_0} \right) \right]^3 \exp \left( -b_s (\Delta \Theta) \right) \]  

(17)

Based on Mohr-Coulomb failure criterion, the strain of coal caused by the changes of geostress and gas pressure is written as the follow equation.

\[ G \sum_{j=1}^{3} \frac{\partial^2 \mu_i}{\partial x_j^2} + G \sum_{j=1}^{3} \frac{\partial^2 \mu_j}{\partial x_i \partial x_j} + \frac{3M - 2G}{3K} \frac{\partial p}{\partial x_i} + \alpha \frac{\partial p}{\partial x_i} + F_i = 0 \]  

(18)

where \( G \) is the second order Lame coefficient; \( u_i \) and \( u_j \) are the descending gradients of gas pressure in the \( i, j \) direction, respectively; \( x_i \) and \( x_j \) are the coal displacements in the \( i, j \) direction, respectively; \( \alpha \) is the coefficient of pore pressure; \( F_i \) is the bulk stress in the \( i, \) direction, MPa.

Since COMSOL software employs FEM, a 2D coupled model was meshed to simplify the calculation based on the plain-strain assumption. For the solid deformation model, the left and the right side are set as roller boundaries, the bottom is fixed, and the top is set as the stress boundary with a normal stress of 9 MPa. For the gas flow model, a constant pressure of –23 KPa is applied to the wall of borehole, and no flow conditions are applied on the other boundaries. Regarding the relations between jet velocity, nozzle diameter, initial standoff distance, and the penetration length derived from ALE analysis in the previous chapter, the equivalent radii of borehole after flushing operation were 0.34 and 0.85 m, respectively, in submerged and nonsubmerged conditions. The borehole after flushing is regarded as a uniform cylinder in the model. Thus, the relations between the discharged coal amount and the equivalent radius of borehole by jet cutting were interpreted as follow:

\[ \frac{m}{\gamma} + \pi r_0^2 L = \pi r_1^2 L \]  

(19)

where \( m \) is the mass of discharged coal, \( t \); \( \gamma \) is the apparent density of coal, \( t/m^3 \); \( r_0 \) is the initial radius of borehole, m; \( r_1 \) is the equivalent radius of borehole after waterjet operation, m; and \( L \) is the length of discharged coal, m.

3.2 Numerical results

The differences of drainage effect between submerged and nonsubmerged conditions were shown in Figure 11. The effective drainage radii of submerged waterjet at the period of 1, 3, and 6 months were 0.92, 1.98, and 2.94 m, respectively. In contrast, that of nonsubmerged waterjet was 1.33, 2.83, and 4.02 m, respectively, at the period of 1, 3, and 6 months. It can be inferred that the nonsubmerged waterjet not only produces a larger cavity of gas pressure relief than the submerged waterjet, but also causes more loose deformation and creep in surrounding coal. Consequently, the permeability improvement of nonsubmerged waterjet is more significant, resulting in a larger effective drainage radius. Additionally, the effective drainage radius increases with prerecovery time. However with the attenuation in gas flow, the increasing rate of effective drainage radius gradually slows down after 3 months.

4 FIELD TRIAL

4.1 Field situation and waterjet operation

Liulong coal mine is located in the east of Liupanshui coalfield, (Pingzhai town, Liuzhi special district, Guizhou Prov. 553400, China), and its production capacity is about 300 thousand tons of meager-lean coal annually. Nowadays, the coal mine is mainly recovering No. 7 coal seam (the average thickness of 6.4 m and the dip angle of 32°) belonging to the Permian Longtan Formation. Since the shaft area is situated in the junction area of tectonic forces (between the northeastern flank of Liuzhi syncline and the ridge of Meizi anticline), the permeability of No. 7
FIGURE 11  Drainage effects of two jet patterns at different periods

FIGURE 12  Layouts of No. 1075 drainage tunnel and drilling field
coal seam is extremely low. In order to eliminate the risk of coal and gas outburst during the excavation period of No. 1075 tailgate roadway, cross-measure boreholes were drilled from No. 1075 drainage roadway to recover coalbed gas within the range between 20 m away from the upper rib of mining roadway and 10 m away from the lower rib. Considering the differences in drainage effects of submerged and nonsubmerged waterjet deduced from numerical results, the spacing of downward and upwards borehole was set at 4 and 5 m, respectively. The layout of drilling field was shown in Figure 12.

The waterjet system, shown in Figure 13, is mainly composed of a integrated bit of drilling and flushing, a hydraulic nozzle, high-pressure sealing drill pipes, an outburst preventer, a driller, a high-pressure switch, a coal-water separator, and the hydraulic pumping unit. The complete process of waterjet for gas recovery was strictly conducted as follows. Firstly, a cross-measure borehole was drilled with hydrostatic pressure to uncover No. 7 coal seam. Then, a high-pressure switch was installed on the end of drill pipes to replace the hydrostatic one without backing drill pipes out, and the nozzle can be automatically opened when hydraulic pressure exceeding 5 MPa. During the flushing process, drill pipes were rotationally propelled at a constant speed and the surrounding coal was broken and discharged by the high-pressure waterjet of 20 MPa. The nozzle diameter is 1.5 cm, and the initial standoff distance is 2 cm derived from the above ALE analysis. After waterjet cutting operation, each borehole must be sealed timely in 2 days to prevent the pressure-relieved gas gushing into roadway.

4.2 Drainage verification

Drainage parameters of borehole, including gas concentration, drainage pressure of pipe, the pipe diameter, and the flow velocity of gas, were totally monitored for 90 days. The total boreholes in No. 67 drilling field were temporarily sealed, so that we can conduct waterjet cutting to investigate the differences in drainage effect after the gas flowrate attenuation.

Figure 14 illustrates before waterjet operation, the gas flowrate in original borehole reduced rapidly in a short period about 25 days. After flushing, a large amount of pressure-relieved gas seeped into fractures in coal matrix, resulting in a significant improvement in gas flowrate. The flowrate of pure gas increased from 0.064 to 0.125 m³/min on average in 90 days.

To examine the regional outburst prevention effect, measurement boreholes were drilled from No. 1075 drainage roadway to determine the gas residual content of No. 7 coalbed after 3 months. As shown in Table 2, all values of gas residual content are less than the critical index of outburst risk (6 m³/t) in Guizhou Prov. and the maximum is 5.02 m³/t. Besides, the
desorption index of drilling debris ($K_1$) fluctuates within the range of 0.04-0.37 mL/g·min$^{1/2}$ during the excavation of No. 1075 tailgate roadway, and the maximum is 0.37 mL/g·min$^{1/2}$ less than the critical index of 0.5 mL/g·min$^{1/2}$. The amount of drilling debris ($S$) is about 1.7-2.1 kg/m, less than the critical index of 6 kg/m. Furthermore, the dynamic phenomena such as borehole spraying, sticking and jamming in drilling never happened in the excavation process. Consequently, the reservoir stimulation using submerged waterjet technique guided by ALE analysis achieved purpose of enhancing the gas recovery efficiency, meanwhile greatly shortening the prerecovery period.

5 | CONCLUSION

It is of vital importance to investigate the effects of coal cutting performance by using submerged waterjet in downward boreholes on gas recovery for a reasonable layout of drilling field. The coal cutting performances under different jet conditions are investigated with the ALE algorithm assistance. Next, a coupled model of gas flow was built to study interactions of the discharged coal amount with COMSOL software. The following conclusions can be drawn from the simulation results.

(a) Under submerged conditions, waterjet can flush coal in a very short time, forming a funnel shape erosion pit, and the cutting performance in initial stage of 0-100 μs is the highest. In contrast, the nonsubmerged jet always holds linear to impact coal, and the penetration length is much larger than that of submerged jets. (b) Under submerged conditions, the penetration length increases with the jet velocity rising from 180 to 210 m/s. Further, the coal cutting performance has also been improved with the increased nozzle diameter and the shorter standoff distance. (c) The effective drainage radii of submerged and nonsubmerged waterjet in 3 months are 1.98 and 2.83 m, respectively, and the increasing trend slows down after 3 months with the gas flow attenuation. (d) After the waterjet operation in No. 1075 drainage tunnel, the gas flowrate increases from 0.064 to 0.125 m$^3$/min on average in 3 months. Consequently, the reservoir stimulation using submerged waterjet technique achieves an ideal effect of enhancing gas recovery production, meanwhile greatly shortening the prerecovery period.

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NOMENCLATURE

| ALE | Arbitrary Lagrange-Euler |
| A | Normalized cohesive strength (Table 1) |
| C | Strain rate coefficient (Table 1) |
| $F_c$ | Uniaxial compressive strength (Table 1) |
| $E F_{\text{min}}$ | Plastic strain before fracture (Table 1) |
| $P_c$ | Cutoff pressure (Table 1) |
| $P_L$ | Locking pressure (Table 1) |
| $D_1, D_2$ | Damage constant (Table 1) |
| $E$ | Initial inner energy (Table 1) |
| $\alpha$ | Correction coefficient (Table 1) |
| $G$ | Shear modulus (Table 1) |
| $B$ | Normalized pressure hardening (Table 1) |
| $N$ | Pressure hardening exponent (Table 1) |
| $T$ | Tensile hydrostatic pressure (Table 1) |

### TABLE 2 Gas residual content in verification boreholes

| Borehole No. | Location | Gas components/% | Residual content/(m$^3$/t) |
|--------------|----------|------------------|-----------------------------|
|               |          | CH$_4$ | N$_2$ | CO$_2$ |                  |
| I             | Between No. 45-46 drilling field | 87.65 | 7.62 | — | 3.65 |
| II            | Between No. 57-58 drilling field | 96.88 | 1.37 | — | 4.83 |
| III           | Between No. 63-64 drilling field | 88.62 | 9.05 | — | 5.02 |
| IV            | Between No. 69-70 drilling field | 82.39 | 16.50 | — | 3.79 |
| V             | Between No. 75-76 drilling field | 84.12 | 11.10 | — | 4.26 |
| VI            | Between No. 84-85 drilling field | 23.09 | 65.28 | — | 1.65 (Leakage) |
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CONFLICT OF INTEREST

I declare on behalf of my coauthors that no conflict of interest exists in the submission of this manuscript.

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