A liquid-solid model to optimize the application of friction reducers for hydraulic fracturing/cutting in the underground coal mine

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Funding information
Chongqing technology innovation and application demonstration (social livelihood) general project, Grant/Award Number: cstc2018jscx-msybX0067; Special funds for scientific and technological innovation and entrepreneurship of Chongqing Research Institute of China Coal Technology and Engineering Group Corp., Grant/Award Number: 2018ZDXM05; 2019YBM30; Tiandi technology co. LTD Special funds for scientific and technological innovation and entrepreneurship, Grant/Award Number: 2019-TD-MS017 and 2019-TD-QN038

Abstract
Friction reducers are widely applied to reduce friction losses in the natural oil and gas industry. The application of hydraulic fracturing in underground coal mines results in a new issue for friction reducers: The hydraulic fluid, mixed with a friction reducer, should reduce friction loss to maintain the hydraulic pressure while simultaneously discharging coal particles to clean the borehole. Most previous studies have focused on the former aspect, ignoring the discharge capacity of coal particles. To compensate for this shortcoming, a coupled flow model of coal particles and hydraulic fluid is proposed considering the interactions between the two phases and characteristics of the coal particles. The model was implemented and solved using the finite element method approach (COMSOL Multiphysics), and the impact of the injection velocity, hydraulic fluid viscosity, and stacking angle of coal particles was investigated. Before simulation, an experiment was conducted to determine the viscosity range and velocity dependency of the hydraulic fluid with a flow-loop instrument. A field application was conducted based on simulation results. The viscosity of 2.5 mPa s is a critical value around which the maximum friction reduction efficiency can be achieved, and the discharge capacity of coal particles can be enhanced significantly above this value. The applications of hydraulic fracturing or hydraulic cutting should be coupled with the viscosity of the hydraulic fluid. The injection velocity should be sufficiently high, and the time interval of the water spray should be sufficiently large for the low-viscosity hydraulic fluid. The stacking angle of the coal particles has little influence on the long-term discharge process. An upward borehole is recommended for the consideration of coal particle discharge because of the gravity effect. This work provides constructive suggestions and guidance for underground hydraulic fracturing and hydraulic cutting.

Keywords
friction reducers, viscosity, coal particles, finite element method
1 | INTRODUCTION

The efficient exploration and utilization of coalbed methane (CBM) is essential for mitigating the energy crisis, ensuring mine safety, and reducing environmental pollution. However, the anticipated expectations are not met because of the low permeability of the coal seams. Hydraulic fracturing (HF) and hydraulic cutting (HC) are widely applied to enhance the extraction efficiency of CBM by enlarging the contact area between the depleted gas pressure and reservoir. However, during the application of these methods, a significant amount of hydraulic fluid (slick water), opponents, and activators are injected into the reservoir via well holes or borehole. HF and HC coal particles are more likely to be deposited at the lower part of the annulus, forming a cutting bed under the action of gravity. This type of deposition leads to severe issues during extraction such as stuck drilling, lost circulation, and blocking of the gas flow channel. Under these conditions, the viscosity of the slick water should be sufficient to carry out the coal particles. Therefore, friction reducers (FRs) are essential during CBM mining to reduce friction loss and remove coal particles from the bore hole or well hole. The benefits associated with the use of friction reducers have prompted the development of high-efficiency FRs for underground coal mines.

Because of the development of the oil and natural gas industry, new types of FRs have been widely developed and applied in recent years. Related studies have suggested the existence of an optimal viscosity range of slick water around which maximum friction reduction could be achieved. The associated two-phase flow of the solid (coal particle)-liquid (slick water) interaction has been widely studied, especially in petroleum engineering (drilling or proppant transport). Three critical physical phenomena that affect the hydrodynamics of particle transport in the fluid are fluid drag, particle-particle, and particle-wall interactions. In fluid drag, the continuous phase exerts a drag force on the particles, changing the particle transport velocity. Moreover, the particle travels slowly compared with the fluid because of the drag force and energy dissipation, resulting in slippage velocity and adding complexity to the flow. In addition, based on the concentration of suspended particles, interparticle collisions can significantly affect the transport phenomenon. Increased interparticle collisions occur in the dense phase transport, increasing the randomness and turbulence in the flow and contributing to the complexity of the flow. Lastly, for the slurry flow in rough wall surfaces, the irregular wall increases particle-wall interactions and significantly enhances the flow disturbance affecting the hydrodynamic and mechanical properties of solid transport.

The numerical approaches are widely applied because of its advantages of revealing the internal flow mechanism of the solid-liquid two-phase and the flow details that are difficult to obtain experimentally. To capture the physics of coal particle transport in fracturing fluid flow, the two key numerical approaches available in the literature are the Eulerian-Lagrangian method and the Eulerian-Eulerian method. The Eulerian method models the continuous phase by solving the mass and momentum conservation equations, and the solid phase (coal particle) is modeled by tracking particle motion using Newton’s second law of motion. For tracking discrete phases, the Lagrangian and Eulerian methods are coupled to analyze the particle-fluid system issues existing in industry. The two most common Eulerian-Lagrangian methods used in the literature are the discrete particle method (DPM) and the computational fluid dynamics-discrete element method (CFD-DEM). Wang et al. applied the Eulerian-Lagrangian method to model the proppant deposition and transport characteristics in hydraulic fractures and fracture networks. A similar approach was also proposed by Akhshik et al. and Yan et al. to model the cutting transport in underbalanced drilling and provide a detailed analysis of particle-fluid and particle-particle interactions. However Eulerian-Lagrangian methods are computationally costly, providing a challenge to apply it to the field scale. The Eulerian-Eulerian approach is typically represented by the two-fluid model (TFM), whereby the fluid and solid phases (coal particles) are regarded as interpenetrating continuous phases. The TFM approach is typically combined with the kinetic theory of granular flow to describe the interactions between particles. Moreover, this method has relatively smaller computer resource requirements, allowing larger-scale systems with numerous particles to be effectively modeled. Because of these advantages, the Eulerian-Eulerian approach is widely applied in the area of proppant and cutting transport.

The research area in this study is not the same as that in petroleum engineering. During drilling and proppant transport, obtaining the highest viscosity is the primary goal required to achieve the maximum carrying capacity of the proppant while omitting friction loss because a larger fracturing pressure can be achieved through the height difference and application of a multistage pump. For an underground coal mine, the height difference is small, and large equipment cannot be applied because of the limitation of the field condition. Therefore, the capacities of the friction loss reduction and carrying particles should be considered simultaneously. In this study, we focused on the particle carrying capacity of the hydraulic fluid, disregarding the interactions between different particles, and proposed...
a modified TFM in which the drag force is related to the diameter of the coal particles.

2 | MATHEMATICAL MODEL

The modified TFM developed in this study was used to investigate coal particle transport during HF and HC and its influencing factors. The principal objective of this work was to provide a detailed understanding of particle transport considering the effect of viscosity and the injection flow rate of hydraulic fluid, the inclination angle of the borehole, and the stacking angle of coal particles. Moreover, the following assumptions were made to investigate our aims: (a) the coal particles are spherical particles with a uniform size, and (b) the interfacial mass transfer between the cutting phase and liquid phase is negligible.33,35

2.1 | Mass conservation equation

The mass conservation equation of each phase is given by38:

$$\rho_i \left( \frac{\partial}{\partial t}(\alpha_i \rho_i v_i) + \nabla \cdot (\alpha_i \rho_i v_i v_i) \right) = S_{m}$$  (1)

where $\alpha_i$ represents the volume fraction with $\sum_i \alpha_i = 1$, $i$ refers to the liquid ($l$) or solid phase ($s$), $\rho_i$ is the density, $v_i$ indicates the velocity, and $S_{m}$ is the mass of the source term.

2.2 | Fluid momentum equation

The momentum equations for the continuous phase (fracturing fluid), using the nonconservative forms,38,39 are:

$$\frac{\partial}{\partial t}(\alpha_i \rho_i v_i) + \nabla \cdot (\alpha_i \rho_i v_i v_i) = \alpha_i \nabla \cdot \tau_i + \alpha_i \rho_i g - \nabla p - \beta (v_i - v_l) + F_{vm,l}$$  (2)

where $g$ is the vector of gravitational acceleration, $\beta$ is the drag coefficient, $F_{vm,l}$ is the virtual mass force of the drilling fluid, and $P$ is the mixture pressure, which is assumed to be equal for the two phases. In the momentum equations, the viscous stress tensor for each phase is denoted by $\tau$.

The turbulent viscosity of the drilling fluid is calculated using the shear stress transport $k$–$\omega$ model, where $k$ and $\omega$ are the turbulent kinetic energy and the specific dissipation rate.40,41 The transport equations for $k$ and $\omega$ are expressed by Equations (3) and (4) for a low Reynolds number modification42:

$$\frac{\partial}{\partial t}(\rho_{k} k) + \frac{\partial}{\partial x_j}(\rho_{k} k v_j) = \frac{\partial}{\partial x_j} \left( \Gamma_k \frac{\partial k}{\partial x_j} \right) + G_k - Y_k$$  (3)

$$\frac{\partial}{\partial t}(\rho_{\omega} \omega) + \frac{\partial}{\partial x_j}(\rho_{\omega} \omega v_j) = \frac{\partial}{\partial x_j} \left( \Gamma_{\omega} \frac{\partial \omega}{\partial x_j} \right) + G_{\omega} - Y_{\omega} + D_{\omega}$$  (4)

where $G$ is the generation due to mean velocity gradients, $\Gamma$ is the effective diffusivity, $Y$ is the dissipation due to turbulence, and $D$ is the cross-diffusion term.

Similarly, the momentum equations for the coal particles can be written as:

$$\frac{\partial}{\partial t}(\alpha_s \rho_s v_s) + \nabla \cdot (\alpha_s \rho_s v_s v_s) = -\alpha_s \nabla p + \nabla \cdot (\alpha_s \rho_s g + \beta (v_i - v_s)) + F_{vm,s}$$  (5)

where the symbols denote the same parameters provided in Equation (2).

2.3 | Drag force modeling

Particle, droplets, and bubbles in the fluid flow are affected by a number of forces, such as the drag force, added mass force, Basset force, and lift force. The drag force is typically the most important force affecting the components of fluid flow, particularly in fluids with a high concentration of dispersed solids; thus, this is the predefined force included in the Euler-Euler model.

Gidaspow41 proposed a flexible drag force model that can be applied for a wider application range based on the coal particle volume fraction. The Gidaspow drag model is used in this study and is described by (6):

$$\beta = \begin{cases} 150 \alpha_s (1-\alpha_s) \mu_1 + 1.75 \frac{\alpha_s \rho_s |v_s - \bar{v}_s|}{d_s} & \text{if } \alpha_s > 0.2 \\ \frac{3}{4} \frac{C_D \rho_1 \alpha_s \alpha_i |\bar{v}_s - \bar{v}_l|}{d_s} & \text{if } \alpha_s < 0.2 \\ \end{cases}$$  (6)

where $d_s$ represents the solid-phase diameter, and $C_D$ is the drag coefficient calculated by Equation (7)35:

$$C_D = \begin{cases} \frac{24}{\alpha_i \cdot Re_s} & [1 + 0.15(\alpha_i \cdot Re_s)^{0.687}] & \text{if } \alpha_i \cdot Re < 1000 \\ 0.44 & \text{if } \alpha_i \cdot Re > 1000 \end{cases}$$  (7)

where $R_s$ refers to the Reynolds number of the solid phase and calculated by43:

$$Re = \frac{\rho d_s |\bar{v}_s - \bar{v}_l|}{\mu}.$$  (8)
2.4 Stress model for the coal particle phase

Savage and Jeffrey\textsuperscript{44} described that the solid stress for the coal particle phase, $\tau_s$, is based on the kinetic theory of granular flow (KTGF) models, as expressed in Equation (9)\textsuperscript{43}:

$$\tau_s = (-P_s + \lambda_s \nabla \cdot \mathbf{u}_s)I + \mu_s \left\{ [\nabla \mathbf{u}_s + (\nabla \mathbf{u}_s)^T] - \frac{2}{3} (\nabla \cdot \mathbf{u}_s) I \right\}$$

(9)

where $\lambda_s$ and $\mu_s$ refer to the bulk viscosity and dynamic viscosity of the granular phase, respectively, $I$ is the unit tensor, and $p_s$ indicates the solid-phase pressure.

2.5 Granular temperature

The granular temperature is one of the critical parameters for modeling coal particle–laden fluid flow, as it is a function of the specific kinetic energy of the particle velocity fluctuations, as expressed in Equation (10)\textsuperscript{33}:

$$\Theta_s = \frac{1}{3} \mathbf{v}_s^2$$

(10)

where $\Theta_s$ refers to the granular temperature, and $\mathbf{v}_s$ refers to the granular phase velocity fluctuation. Thus, the granular energy transport equation is given by Equation (11)\textsuperscript{33}:

$$\frac{3}{2} \left[ \frac{\partial}{\partial t} (\alpha_s \rho_s \Theta_s) + \nabla \cdot (\alpha_s \rho_s \Theta_s \mathbf{v}_s) \right] = (-P_s I + \tau_s) : \nabla \mathbf{v}_s + \nabla \cdot (\kappa \nabla \Theta_s) - \gamma_{\Theta_s} \Phi_{ls}$$

(11)

where $\Phi_{ls}$ refers to the interphase granular energy transfer, $\gamma_{\Theta_s}$ is the granular energy dissipation rate due to an inelastic collision, $\kappa$ is the diffusion coefficient, and $\alpha_s$ is the granular phase volume fraction. Van Wachem et al\textsuperscript{45} proposed an algebraic expression, described by Equation (12), assuming a steady-state solution of the granular energy and neglecting the convection and diffusion terms.

$$0 = (-P_s I + \tau_s) : \nabla \mathbf{v}_s - \gamma_{\Theta_s} \Phi_{ls}$$

(12)

2.6 Granular phase pressure model

For fluid-solid mixtures, such as solid particles in liquid flow, a model for the solid pressure is required. The solid pressure models the particle interaction due to collisions and friction between the particles. Lun et al\textsuperscript{46} proposed a correlation for calculating the pressure for the granular phase, $P_s$, which relates to the normal force acting as a result of particle motion, as described by Equation (13):

$$P_s = \rho_s \alpha_s \Theta_s + 2 \rho_s \alpha_s^2 \Theta_s (1 + e_{ss}) g_{0,ss}$$

(13)

where $e_{ss}$ refers to the restitution coefficient due to particle collision, which can vary from 0 to 1, corresponding to a perfectly inelastic to a perfectly elastic collision. In this study, an inelastic particle collision with a restitution coefficient of 0.9 is assumed in this study, based on the study of Basu et al.\textsuperscript{47} Lun et al\textsuperscript{46} proposed a model for the probability radial distribution function of particles contacting another particle $g_{0,ss}$ given by the following equation:

$$g_{0,ss} = \left[ 1 - \frac{a_s}{a_{s,\text{max}}} \right]^{-1}$$

(14)

where $a_{s,\text{max}}$ refers to the maximum packing limit of the granular phase. It was described by Lun et al\textsuperscript{46} that for uniform coal particle size, the maximum packing is 0.63. The present study also deals with identical sized coal particles, and thus, a 0.63 maximum packing limit is used.

2.7 Granular shear viscosity

The granular shear viscosity is a vital parameter and is modeled as the sum of the kinetic $\mu_{s,\text{kin}}$, collisional $\mu_{s,\text{col}}$, and frictional viscosity $\mu_{s,\text{fr}}$, as expressed in Equation (15):

$$\mu_s = \mu_{s,\text{kin}} + \mu_{s,\text{col}} + \mu_{s,\text{fr}}$$

(15)

models given in Equations (16)–(18), respectively, were used to account for the kinetic viscosity, collisional viscosity, and frictional viscosity.

$$\mu_{s,\text{kin}} = \frac{10 \alpha_s d_s \sqrt{\Theta_s \pi}}{96 \alpha_{s,\text{min}} \left(1 + e_{ss}\right)} \left[1 + \frac{4}{5} \alpha_s g_{0,ss} (1 + e_{ss}) \left( \Theta_s \pi \right)^{\frac{1}{2}} \right]^2$$

(16)

$$\mu_{s,\text{col}} = \frac{4}{5} \alpha_s \rho_s d_s g_{0,ss} (1 + e_{ss}) \left( \Theta_s \pi \right)^{\frac{1}{2}}$$

(17)

$$\mu_{s,\text{fr}} = P_d \sin \theta$$

(18)

where $\theta$ refers to the angle of friction, defined as 30, and $P_d$ refers to the friction pressure defined by the Johnson and Jackson model described by Equation (19):

$$P_d = F \left( \frac{a_s - a_{s,\text{min}}}{a_{s,\text{min}} - a_s} \right)^n$$

(19)
where the constants $F_r = 0.1\alpha_s$, $n = 2$, and $P = 5$. $\alpha_{s,\text{min}}$ is the granular phase volume fraction at which friction becomes dominant (approximately 0.6) and $\alpha_{s,\text{max}}$ is the maximum packing limit, as explained earlier.

### 3 | NUMERICAL MODEL

In this work, the governing equations of solid (coal particle)-liquid (fracturing fluid) are implemented and solved in COMSOL Multiphysics (Version 5.5). In addition, a flow-loop instrument is designed to determine the suitable viscosity range of the hydraulic fluid and its velocity dependency.

#### 3.1 | Coupling processes

COMSOL Multiphysics can model the shape of the phase boundary between the hydraulic fluid and solid particles in detail using a separate multiphase flow model and surface tracking approach. However, this approach is only available for problems on a small scale. For the two-phase flow of coal particles and injection fluid, the computation cost is high if the same approach is applied. Fortunately, the software offers an alternative method to treat large-scale problems. In this approach, the dispersed multiphase flow model equations are used, and the phase effects (such as surface tension, buoyancy, and transfer across phase boundaries) are considered as the source and sink terms.

The governing equations of the coal particle and fracturing fluid flow are coupled as follows: (a) the coal particle flow and fracturing fluid are coupled through the drag force, as specified in Equations (6)-(8), and (b) the coal particle flow is related to the viscous stress tensor with Equations (8) and (9), and the granular shear viscosity with Equations (15)-(19) (c), which are both related to the granular temperature (Equations (10)-(12)) and the granular phase pressure (Equations (13) and (14)). The coupled process is illustrated in Figure 1.

In the COMSOL Multiphysics (Version 5.5), the mixture model, laminar flow interface, was applied to model the flow at low and moderate Reynolds numbers of liquids containing a dispersed phase and solve the mass conservation equation and fluid momentum equation in which the drag force is settled is adapted in this work. Furthermore, the PDE interface is applied to solve the remaining equations, and other variables can be defined in the variable definitions.

#### 3.2 | Geometry-computational domain

At present, gas extraction methods mainly include pre-extraction of gas in the mining and adjacent coal seam, gas extraction in the goaf, and surface vertical well, as shown in Figure 2(A). Generally, the borehole has a diameter of 113 mm with a jack rod with a diameter of 73 mm, as illustrated in Figure 2(B). Therefore, the width of the spare space for the coal particle flow was approximately 40 mm. To reduce the computational cost, the 3D model was simplified into a 2D model. For the geometry, a rectangle with a width of 40 mm and length of 10 m was created to simulate the flow domain, as illustrated in Figure 3(A). The coordinate system is defined as follows: the extension direction of the borehole is defined as the $x$-axis with a positive direction to the right, the vertical direction is specified as the $y$-axis with a positive direction upward, and the original point is located at the lower left quarter. The coal particles are located on the left side of the simulation domain, accounting for approximately 5% of the total volume, as shown in Figure 3(A). Based on the data from literature, the coal particle size is set as 200 μm.

To meet the goal of high meshing quality, a boundary layer is applied to the wall of the simulation model, and a default ‘extremely finer’ is specified to control the mesh size. After meshing, 75 570 elements were drawn with an average element quality of 0.88. The elements near the phase surface are shown in Figure 3(B).

The boundary conditions are specified as follows: (a) the injection velocity is applied to the left side, (b) the reference pressure, 0 Pa, is applied on the right side, and (c) no slip flow boundary conditions are specified for the upper and lower walls. The initial coal particle fraction is 0.5, at the coal particle stacked area and zero at the rest area. The initial hydraulic fluid fraction was zero for the entire area.

#### 3.3 | Viscosity determination

As mentioned above, friction reducers are usually added to reduce the friction loss in which the linear glue, high polymer, emulsion polymer, and crosslinked polymer are mostly
applied. Guar gum, UG-3, DR-12, and EM30, belonging to the four categories mentioned above, were selected to test the friction reduction efficiency and determine the viscosity before the simulation.

An in-house-designed flow-loop instrument was designed to test the efficiency, as shown in Figure 4. An experimental liquid with a friction reducer mass fraction of 0.1% was prepared with four friction reducers and clean water. The results
are shown in Table 1. As illustrated in the figure, the friction reduction capacity can be significantly increased after mixing with the resistance-reducing agents.

A rheometer was used to measure the viscosity and temperature dependency of the four friction reducers with a shear rate of 170 s\(^{-1}\). The maximum value of viscosity during the heating process was recorded, as shown in Table 2. As shown in the table, the friction reduction capacity does not linearly increase with viscosity, and the best suitable range for hydraulic fluid is approximately 2.0-2.5 mPa s.

The velocity dependency of the hydraulic fluid was also determined with the results shown in Figure 5.

**3.4 | Results of benchmark model**

A benchmark model was first established to investigate the two-phase flow process using the parameters listed in Table 3.

For clarity, two reference points, Point A (1 m, 20 mm) and Point B (9 m, 20 mm), and two reference lines, Line A (x = 1 m) and Line B (x = 9 m), are selected. The volume friction of the coal particles at different times is shown in Figure 6.

Figure 6(A) shows the distribution of coal particles in the initial state, and Figure 6(B)-(D) represents the distribution of coal particles at 2 s, 9 s, and 18 s, respectively. As observed from these figures, as time progresses, under the effect of fluid drag, coal particles generally move to the right. In addition, the displacement and velocity of the particles in the middle of the borehole were significantly greater than those on the wall. This is because when water flows in the pipe, owing to the influence of the wall, the velocity in the middle of the borehole is greater than that on the wall, leading to a greater particle velocity in the middle. In addition, with the migration of coal particles, the distribution scope of coal particles in the pipeline becomes wider and more dispersed. Because of gravity, the coal particle fraction lags behind at the bottom wall compared with the upper wall.

Figure 7(A,B) shows the coal particle fraction volume at two different sections (X = 1.4 m and 9 m). In Figure 7(A), at 2 s, the coal particle fraction volume first increased and then decreased with increasing height. At 9 s and 18 s, the volume fraction of coal particles decreased significantly, indicating that most of the coal particles had passed through this area. In Figure 7(B), the coal particle volume fraction is almost zero at 2 s and 9 s, indicating that the particles have not yet migrated to this area at this time. At 18 s, the coal particle fraction volume also showed a similar trend of increasing first and then decreasing with the increase in height.

**4 | PARAMETER SENSITIVITY ANALYSIS**

Based on the results in the literature\(^{51-53}\) and the practice in the field,\(^{54}\) the water injection velocity, viscosity of the injection fluid, stacking angle of the coal particle, and angle of the borehole would significantly impact the two-phase flow
characteristics. The following scenarios were designed to test the parameter sensitivities, as listed in Table 4. For comparison, the dimensionless amount of discharged coal particles was specified as follows:

\[ Q_d = \int_0^t q_t \, dt / Q_t \]  

(20)

where \( q_t \) represents the flow rate of the coal particle, which can be obtained from the integration of the outlet, and \( Q_t \) is the total coal particle amount.

### 4.1 Impact of water injection velocity

The dimensionless amount of discharged coal particles and the variation in the coal particle volume fraction at two different reference points with varied injection velocities are shown in Figures 8 and 9, respectively. Water injection velocities of 0.1, 0.2, 0.5, 1, and 2 m/s were considered.

As shown in Figure 8(A), the higher the water injection velocity, the steeper the curve. This also means that for a higher water injection velocity, less time is required to discharge the coal particles. To check the time dependency, the times reaching 50 (\( t_{50} \)) and 100 (\( t_{100} \)) of dimensionless amount with injection velocity were recorded, as shown in Figure 8(B). As clearly shown in the figure, a smaller injection velocity results in a longer time, and a larger injection velocity requires a shorter time. Another interesting phenomenon is that the time changes dramatically when the injection velocity is less than 1 m/s, while the time changes little when the value is larger than the value.

As shown in Figure 9, the changes in the coal particle fraction at the two reference points with time are similar to the variations shown in Figure 7. The closer it is to the nozzle, the greater the peak value of the particle fraction. With an increase in the water injection velocity, the peak value of the discharged coal particle fraction at the same reference point gradually decreases. For different hydraulic fluid injection rates, the decreasing trends of the discharged coal particle fraction at the same reference point are similar.

### 4.2 Impact of hydraulic fluid viscosity

As demonstrated in the previous section (Section 3.3), the viscosity of the hydraulic fluid ranges from 1 to 3 mPa s when friction reducers are added. Therefore, five different sets of comparative viscosity data (1, 1.5, 2, 2.5, and 3 mPa s) were set up to investigate the impact of hydraulic fluid viscosity on the discharge ability of coal particles, and the results are shown in Figure 10(A).

There was no significant difference in the amount of discharged coal particles with different hydraulic fluid viscosities, as shown in Figure 10(A). However, from the data, we can still find that the amount of discharged particles increases with the enhanced viscosity. This also means that an increase in the viscosity of the fracturing fluid would enhance the discharge speed of the coal particles. The dimensionless amount of discharged coal particles at different times with varying viscosities is shown in Figure 10(B). The discrepancies between different injection fluid viscosities are large when the time is less than 20 s and then become small when the time exceeds 20 s. A conclusion is drawn that the hydraulic fluid characterized by a large viscosity should be chosen when the water spray time interval is small. When the water spray time interval was large, slight differences in viscosities were observed.

The coal particle volume frictions at the two reference lines are shown in Figure 11. It is not difficult to find that with the increase in viscosity, the peak value of the coal particle volume fraction on the reference line gradually increases at reference
Line A ($x = 1.4 \text{ m}, t = 2 \text{ s}$). Also observed in Line A, the peak is sloped down when the viscosity is low because of the gravity effect. While on the other hand, the volume friction is symmetrically distributed when the viscosity is large. For reference line B, similar observations can be determined, but not obviously.

### 4.3 Impact of stacking angle of coal particles

The stacking angle of coal particles also has an impact on the coupled phase flow of the hydraulic fluid and coal particles.

**FIGURE 7** Coal particle volume fraction at the reference line of (A) Line A, $x = 1.4 \text{ m}$ and (b) Line B, $x = 9 \text{ m}$

**TABLE 4** Designed simulation cases

| Scenario | Parameter meaning                | Unit and Value          |
|----------|----------------------------------|-------------------------|
| I        | Water injection velocity         | 0.1, 0.2, 0.5, 1.2 [m/s]|
| II       | Viscosity of injection fluid     | 1, 1.5, 2, 2.5, 3 [mPa s]|
| IV       | Stacking angle of the coal particle | 10, 30, 40, 50, 60 [°]|
| IV       | Angle of borehole                | 0, 5, 10, 15 [°] upward |
|          |                                  | 0, −5, −10, −15 [°] downward|

**FIGURE 8** (A) Dimensionless amount of discharged coal particles with different injection velocity and (B) time dependency of injection velocity
In this section, the stacking angle varied from 10° to 60° with an interval of 10°. Similarly, the dimensionless amount of discharged coal particles and coal particle fraction volume at two different reference lines are illustrated in Figures 12 and 13, respectively. As illustrated, the coal particle stacking angle has little influence on the dimensionless amount. When we enlarged the figure, we found that the stacking angles of 10° and 40° defined the upper and lower boundaries of the dimensionless amount. However, the differences in the other three stacking angles were not obvious.

In this work, the total amount of coal particles is assumed to be the same for all scenarios, leading to the fact that the smaller the stacking angle is, the wider the distribution range of coal particles is at the initial moment. Therefore, a lower coal particle volume fraction is observed for the small stacking angle at reference line A, $x = 1.4$ m. For line reference Line B, $x = 9$ m, a smaller difference is observed. Based on the above analysis, it can be concluded that the coal particle stacking angle has a significant impact on the initial state of the coal particle distribution, but has little impact on the long-term flow.

4.4 Impact of borehole angle

In addition to the horizontal borehole of the coal seam, the upward and downward boreholes drilled in the tunnel are usually applied in underground coal mines, and the effect of gravity cannot be ignored. Therefore, a series of different borehole angles of the downward/upward borehole are applied to investigate the impact of gravity on the coal particle discharge, and the results are shown in Figure 14. In the figure, the negative means downward borehole with positive...
indicating upward. As shown in Figure 14, the downward borehole takes a large amount of time to discharge the coal particles as the flow direction is opposite to the gravity direction. An interesting characteristic is found in Figure 14(B) that gravity has little influence when the change in angle is small and has a significant impact when the change is large.

An inverse situation is found for the upward borehole: the time to fully discharge the coal particle decreases with the increment in borehole angle because of gravity, as shown in Figure 14(A). In addition, a larger difference results in a shorter time, as demonstrated in Figure 14(B).

4.5 Discussion

In the above sections, the impacts of artificial factors (injection velocity and hydraulic fluid viscosity) and geological factor (stacking angle of coal particles and borehole angle) are investigated. Among the artificial factors, the injection velocity has more significant impact compared with the impact of hydraulic fluid viscosity. Among the geological factor, the borehole angle would significantly impact the discharged efficiency while the stacking angle of coal particles has little impact.

From the numerical results, we also found that the application of hydraulic fracturing or hydraulic cutting should consider both artificial and geological factors: (a) A high injection velocity is necessary for a low-viscosity hydraulic fluid, and a low injection velocity is sufficient for a high-viscosity hydraulic fluid; and (b) gravity enhances the coal particle discharge process, and an upward borehole is recommended for the consideration of coal particle discharge.

5 FIELD APPLICATION

The transport roadway 3308 working face with a stable geological structure in the Wangpo coal mine was selected as the field application area. A total of 30 boreholes were designed to investigate the impact of fraction reducers on methane extraction with a depth of 100 m and spacing of 10 m. Boreholes 1#–5# were common boreholes without hydraulic cutting (group A). Boreholes 6#–40# were hydraulically cut using different hydraulic fluids. Clean water was used as the hydraulic fluid for boreholes 6#–10# (Group B), a fluid with a viscosity of 2.5 mPa s and a velocity of 1.5 m/s is adopted for boreholes 11#–15# (Group C), a fluid with a viscosity of 1.5 mPa s and velocity of 2.5 mPa s and a velocity of 1 m/s is adopted for boreholes 16#–20# (Group D); fluid with a viscosity of 1.5 mPa s and a velocity of 1.5 m/s is adopted for boreholes 21#–25# (Group E), and a fluid with a viscosity of 1.5 mPa s and velocity of 2 m/s is adopted for boreholes 26#–30# (Group F).
The average amount of discharged coal particles is shown in Figure 15. The smallest value was obtained when clean water was selected as the hydraulic fluid. The application of friction reducers can significantly improve the discharged coal particles. Group C had the maximum amount, followed by Groups E, D, and F. However, the difference between Group C and Group E was small.

After hydraulic cutting, all boreholes were connected to extract the methane. The gas flow rate of boreholes within 60 days was investigated, and the average pure gas flow rate of the drilling holes in each group is shown in Figure 16.

The average gas flow rate of common borehole was 0.02 m³/min, while the average gas flow rate of water cutting hole was 0.089 m³/min. The application of friction reducers can significantly increase the flow rate of methane, and the average values of the groups with added friction reducers were all above 0.1 m³/min. Among all friction reducer added groups, Group E and Group C achieved the best result, and Group D and Group F showed slightly worse results.

6 | CONCLUSION

The main goal of this study was to optimize the usage of friction reducers in underground coal mine. To achieve this goal, an experiment was conducted to determine the viscosity...
range of the hydraulic fluid and its velocity dependency. In addition, a two-phase flow model governing the coupled flow of solid (coal particles) and fluid (hydraulic fluid) was established to investigate the discharge process of coal particles. Based on the results, a field application was conducted. Based on the above work, the following conclusions were drawn.

1. The best appropriate range of viscosity for the injection hydraulic fluid should be approximately 2.5 mPa s. Around the value, the maximum friction reduction rate can be achieved, and the discharge capacity of coal particles in a short time can be largely enhanced when the viscosity is larger than the value.

2. The application of hydraulic fracturing technology should be coupled with the properties of the hydraulic injection fluid. A high injection velocity is necessary for a low-viscosity hydraulic fluid, and a low injection velocity is sufficient for a high-viscosity hydraulic fluid. In particular, for underground hydraulic cutting, short intervals of spraying water are suitable for high-viscosity hydraulic fluids, and the intervals must be large for low-viscosity hydraulic fluids.

3. The impact of geological factors was also investigated. The stacking angle of coal particles only affects the initial state of the discharge process and has little influence on the long-term process. Gravity enhances the coal particle discharge process, and an upward borehole is recommended for the consideration of coal particle discharge.

4. As demonstrated in the field test, the application of friction reducers can significantly increase the methane extraction efficiency, and an optimal combination of water injection viscosity and injection velocity exists for hydraulic fracturing/cutting in underground coal mines.

ACKNOWLEDGMENT
This work was financially supported by the Tiandi Technology Co. LTD Special Funds for Scientific and Technological Innovation and Entrepreneurship (2019-TD-MS017, 2019-TD-QN038), Chongqing Technology Innovation and Application Demonstration (social livelihood) General Project (cstc2018jxcx-msybX0067), and Special Funds for Scientific and Technological Innovation and Entrepreneurship of Chongqing Research Institute of China Coal Technology and Engineering Group Corp.(2018ZDXM05, 2019YBXM30), which are gratefully acknowledged.

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How to cite this article: Xiong W, Shen K, Ba Q, Liu Y, Zhou H. A liquid-solid model to optimize the application of friction reducers for hydraulic fracturing/cutting in the underground coal mine. *Energy Sci Eng*. 2021;00:1–15. [https://doi.org/10.1002/ese3.930](https://doi.org/10.1002/ese3.930)