



Coordinated slag Disposal From Horizontal Boreholes During Hydraulic Cutting Based on Two-Phase Flow Theory

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The purpose of the study is to explore the mechanism of coordinated slag disposal in the hydraulic cutting process, ensure the safety implementation of the hydraulic cutting operation and increase the success rate of hydraulic cutting. In the ultra-high pressure hydraulic cutting technique, the method for determining the cutting pressure is ambiguous, the coordination mechanism of various factors (including cutting pressure and coal-dropping speed) lingers unclarified; the slag disposal mechanism during hydraulic cutting is inexplicit. Aiming at these problems, a model for coordinated slag disposal during hydraulic cutting based on coal-water two-phase flow was established. The critical flow velocity in the moving laminar flow regime is taken as that during the coordinated slag disposal from boreholes. The relationship curve between the coal-dropping speed and cutting pressure under different Protodyakonov coefficients of coal seams was obtained. Hence, the model for coordinated slag disposal during hydraulic cutting was established; the selection interval of reasonable pressure for coordinated slag disposal during hydraulic cutting was determined. The reasonable cutting pressure for slag disposal in coal seams with a Protodyakonov coefficient of 0.48 was determined as about 80 MPa. During the cutting test, the average net gas extraction from the boreholes for hydraulic cutting was 4.5 times larger than that from the conventional boreholes. Furthermore, the gas permeability coefficient of the boreholes for hydraulic cutting increased by 25 times; the effective extraction radius was more than doubled. It indicated that the model for reasonably selecting the cutting pressure based on the coordinated slag disposal theory can effectively guide the selection of the cutting pressure on site. While solving various problems occurring in the hydraulic cutting process on site, the model can be used to improve the cutting effect, which provides a theoretical basis for reasonably selecting the pressure during ultra-high pressure hydraulic cutting.

Keywords: hydraulic cutting, cutting pressure, coordinated slag disposal, solid-liquid, two-phase flow

INTRODUCTION

Since 1950s, the average mining depth of coal mines in China has increased by years (Guo et al., 2020; Wang et al., 2021). Up to now, coal mines are still mined downwards at the rate of 8–12 m each year. Therefore, the safe and efficient mining of coal mines is particularly important (Zhang et al., 2019; Liang et al., 2022; Zhang et al., 2022). As deep coal seams in mines are extracted, the high gas and high geostress problems are gradually prominent (Zou et al., 2020; He et al., 2021a). Gas pre-drainage from horizontal boreholes in coal seams, as the most primary method for gas control at present, is widely applied (Hu et al., 2000; Cheng et al., 2009). However, the majority of coal seams in China belong to low-permeability ones, which leads to a poor effect of gas extraction and long time for reaching the extraction standard (Yi et al., 2021; Zhou et al., 2021). It greatly restricts the safe and efficient mining of mines (He et al., 2021b; Zou et al., 2022). Therefore, increasing the permeability of coal seams (Guo et al., 2021; Jia et al., 2021) becomes one of the most primary and effective means to improve the effect of gas extraction and shorten the time for reaching the extraction standard (Wang and Zhang, 2006; Zou et al., 2021).

In recent years, with the research and development of water jet technology, much more hydraulic measures have been applied in coal mines. The ultra-high pressure hydraulic cutting technique has been extensively used in various mine areas in China by virtue of its advantages such as high rated pressure, wide scope of application, simple operation, high safety and obvious local effect. Moreover, scholars all over the world have also explored the permeability-increase mechanism through pressure relief by hydraulic cutting. Yang et al. (2012) simulated the change laws of the stress field in coal seams, gas pressure field and gas extraction efficiency on hydraulic cutting conditions by utilizing Matlab software. The result showed that the stress on coal seams is effectively released after the hydraulic cutting, showing a significant pressure-relief effect; in addition, cracks in coal seams increase greatly in quantity to strengthen the permeability and the adsorbed gas can be effectively released. By simulating the stress release and stress damage in coal around the boreholes for hydraulic cutting, Zhao et al. (2020) analyzed the influences of the uniformity coefficient, Langmuir volume strain constant and overburden stress on damages in coal seams and gas drainage. By comparing the numerically simulated results with the field test data, it can be found that the damage zone in coal induced by the stress relief around the boreholes for hydraulic cutting gradually expands with the growth of the uniformity coefficient and overburden stress; the permeability of coal seams gradually grows with the increase of Langmuir volume strain constant and the reduction of the overburden stress. Shen et al. (2015) explored and analyzed the evolution equations for the effective stress and permeability coefficient as well as pressure-relief and permeability-increase mechanisms during water jet cutting. With the aid of FLAC three-dimensional (3D) percolation model, the evolutions of the effective stress on coal, growth rate of coal permeability and

pore pressure induced by fractures were calculated and analyzed. Additionally, the strengthening effect on permeability through hydraulic cutting and dynamic characteristics of gas drainage from boreholes were investigated through the field test. The results showed that the effective stress on coal obviously drops after the hydraulic cutting and the pressure-relief area around boreholes for hydraulic cutting is 4–7 times larger than that around conventional boreholes. Lin et al. (2015) proposed to prevent and control coal and gas outburst disasters during heading excavation by employing the hydraulic cutting technique. The application of the hydraulic cutting technique on coal can effectively enhance the permeability of coal seams, improve the effect of gas extraction and prevent and control coal and gas outburst disasters during the excavation. Through field tests, it can be found that after the hydraulic cutting, the average coal output from boreholes for hydraulic cutting is 8.2 t and the maximum coal output reaches 16 t. The diameter of boreholes subjected to hydraulic cutting is 12.87 times that of conventional boreholes, which effectively enlarges the impact area of boreholes. After the extraction for half a month, the average gas extraction concentrations from boreholes subjected to hydraulic cutting and conventional boreholes reach 26% and 7%, respectively; it implies that the average gas extraction concentration from boreholes subjected to hydraulic cutting is about 3.7 times larger than that of conventional boreholes.

Scholars in the world have also explored the slag disposal from boreholes. By establishing the models for slag disposal through normal drilling, open-type cave drilling and filled-type cave drilling, Wang et al. (2016) performed the gas-solid coupling dynamic analysis on migration of drilling cuttings in boreholes. The research result indicated that open-type cave drilling marginally affects the migration of drilling cuttings, which only causes a certain pressure loss; the filled-type cave drilling makes the mass fraction of drilling cuttings at the bottom of boreholes multiplies; the drilling cutting particles move along a zigzag path and therefore it takes a longer time to extract them. In the area experiencing the filled-type cave drilling, the instantaneous wave crest of dynamic pressure appears and the differential pressure loss is multiple times of that during the normal drilling and open-type cave drilling. On the basis of investigating the migration law of drilling cuttings during long helical drilling, Yang et al. (1994) proposed a new calculation method for the critical rotational speed and pointed out that the critical rotational speed varies along the radial direction of blades and changes with the feeding rate. Finally, the principle for determining the practical critical rotational speed and the actual rotational speed of drill pipes was discussed. Wei et al. (2017) analyzed the factors influencing the initiation of motion of drilling cuttings and migration law of drilling cuttings on normal drilling and termination of drilling conditions. They found that 1) the critical flow velocity for initiation of motion of drilling cuttings declines with the growth of the hydrate abundance and the value with consideration of hydrate cohesion is larger than that without considering hydrate

cohesion; moreover, the higher the hydrate abundance is, the more significant the influence of hydrate cohesion; 2) with the increase of the size of drilling cutting particles, the critical flow velocity for initiation of motion of drilling cuttings rises in the case that the hydrate abundance is lower than 85% while it drops after the hydrate abundance exceeds 85%; 3) the critical flow velocity for initiation of motion of drilling cuttings reduces with the elevation of the density and viscosity of drilling fluids; 4) the critical return-velocity required by saltation on same conditions is about 1.28 times that on rolling conditions.

In the hydraulic cutting process, coal is cut by high pressure water jets to form nonuniform coal particles, which are mixed with water to form solid-liquid two-phase mixed fluids under the thread effect of drill pipes and gravity effect of themselves. Therefore, it is feasible to analyze the slag disposal from boreholes for hydraulic cutting by utilizing the solid-liquid two-phase flow theory. Scholars all over the world have researched the solid-liquid two-phase flow theory. With the aid of fluent6.3 software, Liu and Zhu (2011) carried out the numerical simulation on the solid-liquid two-phase flow in the centrifugal sewage pump on different working conditions and particles sizes by using Eulerian hybrid model. Through simulation, the distribution law of solid particles in impeller flow passages was attained. The simulation result showed that the distribution law of solid particles in impeller flow passages is mainly related to the particle size. In addition, the particle volume fraction and operation conditions deliver influence on the distribution law of solid particles. The simulation result favorably explains the occurrence of wearing in pump flow passages when transmitting solid-liquid two-phase flow through pumps. Based on the standard model and SIMPLEC algorithm, Li *et al.* (Zhang *et al.*, 2017) conducted the numerical simulation on the surface of micro-voids at different intake rates and further discussed the change laws of the turbulent kinetic energy, dynamic pressure and turbulence intensity in micro flow channels with the intake rate. Shogo Nagaoka *et al.* (Yamaguchi *et al.*, 2011) proposed a method for measuring the solid-liquid two-phase flow based on measurement of electromagnetic signals. By comparing the visual results under three flow regimes (pseudo-homogeneous flow, inhomogeneous flow and inhomogeneous flow + sliding bed flow), the effectiveness of the method was validated. Pelin Ilker *et al.* (Ilker and Sorgun, 2020) conducted numerous computational fluid dynamics (CFD) simulations and test analysis on solid-liquid two-phase flows in wire-bore tubes, eccentric annulus and concentric annulus. The accuracy of the turbulence model is verified by test results and the data provided by Sorgun in 2010. The CFD simulation result well matches with the test results. The results showed that the RNG k - ϵ model exhibits a favorable simulation result on the water flows in wide-bore tubes and eccentric annulus. For water flows in concentric annulus, the EARS model is superior to the other turbulence models. Kramer *et al.* (2020) proposed a relation applicable for calculating the effective resistance to solid-liquid fluidization in actual devices based on the new insight into influences of the spatial and temporal heterogeneity on the effective fluid resistance of large-scale fluidized systems. Through CFD

simulation on the nonuniform distribution of solids, it is possible to increasingly accurately predict the inhomogeneous flow behaviors. However, it is not feasible to perform the computational-intensive simulation for the operation of many large-scale application programs. Therefore, the resistance relationship at full size is obviously needed to effectively consider the spatial distribution of heterogeneous and irregular particles. By measuring related friction coefficient, pressure loss and the transmission rate of particles, Han *et al.* (2020) suggested that the volume and concentration of particles are influenced by in-pipe flow. By exploring the conditions of homogeneous sand with 2 mm in concentric annulus with different inclinations with the ratio of the inner to outer pipe radius of 0.7, the test and numerical results of solid-liquid two-phase flow with fully developing non-Newtonian fluids in different carboxymethylcellulose (CMC) solutions were obtained. It was determined that both the transmission ratio and pressure loss are directly related to the drilling efficiency in the directional boreholes.

The slag disposal process is the most important during the hydraulic cutting in boreholes drilled along seams. However, researchers and scholars in the world have not clearly understood the selection of technological parameters for slag disposal through ultra-high pressure hydraulic cutting technique currently. Especially, selection of the cutting pressure in coal seams with different Protodyakonov coefficients and the coupling relationship between the cutting pressure and slag disposal with drill pipes during the hydraulic cutting have not been clearly understood. The cutting pressure is considered as one of the most important parameters of ultra-high pressure hydraulic cutting technique. Selecting an extremely low cutting pressure cannot break coal or reach the expected cutting depth; however, quite a high cutting pressure leads to too large instantaneous coal output and further triggers borehole outburst and borehole jamming to affect the normal construction, which induces gas exceeding the limit and even threatens workers' safety. The level of the cutting pressure not only influences the coal-dropping speed during the hydraulic cutting but also directly determines the water flow rate in boreholes, thus influencing the slag-disposal capacity from boreholes. Therefore, investigation on the selection of reasonable cutting pressure is significant for successful implementation of hydraulic cutting and improvement of the subsequent extraction effect.

MOTION CHARACTERISTICS OF COAL PARTICLES DURING HYDRAULIC CUTTING

Annular Solid-Liquid Two-Phase Flow Model

Whether coal cinders can be successfully discharged during the ultra-high pressure hydraulic cutting or not influences the cutting effect. The slag-disposal effect of hydraulic cutting is synergistically affected by various factors such as the hardness of coal seams, water jet pressure and flow rate. During the ultra-high pressure hydraulic cutting, coal is cut by high pressure water jets into nonuniform

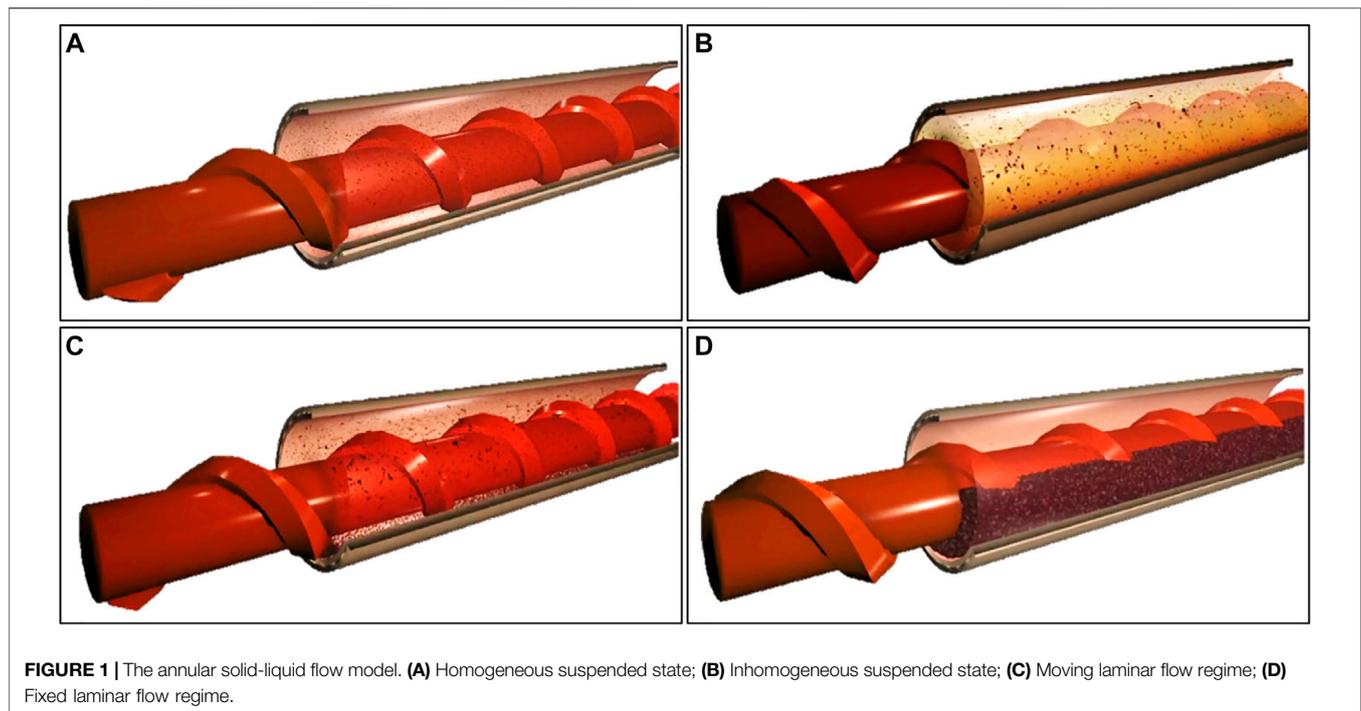


FIGURE 1 | The annular solid-liquid flow model. **(A)** Homogeneous suspended state; **(B)** Inhomogeneous suspended state; **(C)** Moving laminar flow regime; **(D)** Fixed laminar flow regime.

particles, which are mixed with water to form solid-liquid two-phase mixed fluids under the thread effect of drill pipes and gravity effect of themselves. Moreover, the annular space between the drill pipes and hole walls serves as the channel for mixed fluids and therefore it is feasible to theoretically analyze the slag disposal condition during hydraulic cutting by utilizing the theoretical model for annular solid-liquid two-phase flow.

When solid-liquid two-phase fluids flow through the annular channel of boreholes, four different flow regimes (homogeneous suspended state, inhomogeneous suspended state, moving laminar flow regime and fixed laminar flow regime) may occur according to the difference of the concentration of coal particles and the flow velocity, which is shown in **Figure 1**.

The homogeneous suspended state means that coal particles are completely uniformly diffused in liquids (**Figure 1A**). The flow model cannot be formed unless coal particles show a small size and small mass and are transported at a high speed in the completely turbulent state. In most cases, coal particles are in an inhomogeneous suspended state. On this condition, the concentration of coal particles in liquids presents a gradient along the cross section of the liquids, in which the **Figure 1B** concentration at the bottom is higher than that on the top (**Figure 1B**). With the reduction of the flow velocity and the growth of the particle density, the particles with a large size start to deposit at the bottom of liquids, thus forming a deposition layer. Within a certain transporting range, the deposition layer slides in liquids along the flow direction while coal particles above the layer flow at an inhomogeneous suspended state, which is called moving laminar flow regime (**Figure 1C**). As the flow velocity further drops, more coal particles deposit at the bottom of the boreholes and finally a fixed deposition layer is formed at the bottom, which is called the fixed laminar flow regime (**Figure 1D**).

Mechanical Analysis of Coal Particles in Various Motion Stages

According to the motion states of coal particles in coal-liquid two-phase flow from low to high flow velocities, coal particles experience four motion stages, including initiation, rolling, sliding and suspending stages.

Initiation Stage

The particles in the surface layer of coal particle groups generally roll in the initiation stage. Therefore, it is possible to explore the problem of coal particles in the initiation stage by performing the mechanical analysis on a single coal particle.

The force driving the sliding of the coal particle is calculated as follows:

$$F_d = F_D + F_g'' - F_f \quad (1)$$

The resistance to the coal particle is expressed as follows:

$$F_f = \mu(F_g' - F_L) \quad (2)$$

where, μ denotes the coefficient of sliding friction.

It can be obtained that coal particles are subjected to the effects of two force moments at the moment of rolling, which are separately expressed as follows:

The force moment driving the rolling of coal particles is calculated as follows:

$$M_d = F_D \cdot l_1 + F_L \cdot l_3 + (F_g'' - F_f) \cdot l_4 \quad (3)$$

The force moment resisting the rolling of coal particles is expressed as follows:

$$M_r = (F_g'' - F_L) \cdot l_3 \quad (4)$$

To make coal particles roll, it is necessary to satisfy $F_f > F_d, F_g' > F_L$ and $M_d > M_r$.

Rolling Stage

After coal particles roll, the drag force of water flow on coal particles constantly rises with the growing velocity of the water flow field, thus prompting more coal particles to roll. As a result, the motion of a single or multiple coal particles progressively transforms to rolling motion of coal particle groups.

Sliding Stage

As the velocity of the water flow field continues to grow, the force moment of rolling particles reverses, that is, $M_r > M_d$. This is because the growth of the flow velocity results in the constant reduction of the uplift force F_L and the growth of the fluctuating lift of water flows. However, coal particles cannot be in the suspended state owing to the effective gravity of the coal particles still dominates; nevertheless, the friction force between particles drastically reduces, thus leading to reversal of the force moment. The increase of the velocity of the water flow field also causes the drag force F_D of water flows parallel to the water flow direction to grow and gradually dominate, that is, $F_d > F_f$. Therefore, the motion state of coal particles is changed from the previously rolling state to sliding state when the velocity of the water flow field reaches a certain level. In this case, the relationship of forces on particles can be expressed as follows:

$$F_D > \mu \sum_{i=1}^n mg \cos \theta \quad (5)$$

Suspending Stage

After the velocity of the water flow field further increases on the basis of the sliding stage, the turbulence of the water flow field is further strengthened and the fluctuating lift of water flows constantly increases. Eventually, the fluctuating lift is larger than the effective gravity of coal particles and therefore coal particles are in the suspending state. In this context, the force condition of coal particles is calculated as follows:

$$F_g < F_t \quad (6)$$

where, F_t denotes the average fluctuating lift of coal-cinder particles within boreholes.

According to the research results obtained by scholars in China, the average fluctuating lift of water flows is expressed as follows:

$$F_t = -\frac{\xi \tau_f}{\tau_s} \frac{\partial}{\partial y} \left[nm \overline{v_d'^2} \right] \quad (7)$$

where, ξ and τ_f refer to the comprehensive coefficient of coal particles and the characteristic time of fluctuating water flows, respectively; $\tau_f = 0.4L^2 Re_w^{-7/8} \nu^{-1}$, in which L , Re_w and ν represent the flow scale, Reynolds number of water flows and the viscosity

coefficient during the motion, respectively; τ_s denotes the relaxation time of coal particles, satisfying $\tau_s = \rho_s d_s^2 (18\rho_w \nu)^{-1}$; $\overline{v_s'}$ stands for the average fluctuating component velocity of coal particles in the vertical direction and n and m separately refer to the number density and mass of a single coal particle, satisfying $nm = C_v \rho_s$.

It can be found that the solid-liquid two-phase flow in boreholes should be in a moving laminar flow regime in order to successfully discharge coal-cinder particles from the borehole orifice during the hydraulic cutting. In the case, the coal-cinder particles at the bottom of boreholes slide. If the concentration of coal particles or the flow velocity further declines, the motion state of coal particles in boreholes varies from the sliding state to rolling state. Furthermore, large-size coal particles start to deposit at the bottom of boreholes, thus further causing the borehole jamming. Therefore, the minimum flow velocity in boreholes should be the critical flow velocity at the moving laminar flow regime to ensure the successful drainage of coal cinders.

RELATIONSHIP BETWEEN CUTTING PRESSURE AND COAL BREAKING DURING HYDRAULIC CUTTING

Relationship Between Cutting Pressure and Flow Rate

The dynamic pressure of water jets at the nozzle outlet is calculated as follows:

$$P_0 = \frac{1}{2} \rho_0 v_0^2 \quad (8)$$

where, where P_0 , ρ_0 and v_0 separately represent the dynamic pressure at the nozzle outlet, the water density and the axial velocity at the nozzle outlet.

When water jets are just ejected out of the nozzle outlet, it is thought that the velocities at different positions of jets keep unchanged (being the axial velocity). Thus, the relationship between the jet flow rate and the velocity is expressed as follows:

$$Q = \frac{1}{4} \pi d^2 v_0 k_0 \quad (9)$$

By synchronously calculating Eqs. 11, 12, it can be attained that:

$$Q = \frac{1}{4} k_0 \pi d^2 \sqrt{\frac{2P_0}{\rho_0}} \quad (10)$$

where, k_0 and d denote the nozzle coefficient (0.95) and the nozzle diameter (2.5×10^{-3} m), respectively.

Relationship Between Cutting Pressure and Coal-Dropping Speed

To analyze the relationship between different cutting pressure and coal-dropping speed during the cutting in coal seams with different Protodyakonov coefficients, the field test was carried out

TABLE 1 | Basic conditions of the test mines.

Name of coal mines	Main working coal seams	Protodyakonov coefficient of coal seams	Number of test boreholes
Xuehu coal mine	2-2 [#] coal seam	0.2–0.3	24
Zhaozhuang coal mine	3 [#] coal seam	0.3–0.5	16
Yuwu coal Mine	3 [#] coal seam	0.5–0.8	20
Zhaogu No. 2 mine	2-1 [#] coal seam	1.0–1.5	15

TABLE 2 | The coal-dropping speeds in coal seams with different Protodyakonov coefficients under different cutting pressures.

Pressure <i>f</i> values	40 MPa	50 MPa	60 MPa	70 MPa	80 MPa	90 MPa	100 MPa
0.2–0.3	0.054	0.083	0.104	0.143	—	—	—
0.3–0.5	—	0.035	0.056	0.092	0.119	—	—
0.5–0.8	—	—	0.019	0.030	0.051	0.068	—
1.0–1.5	—	—	—	—	0.021	0.031	0.042

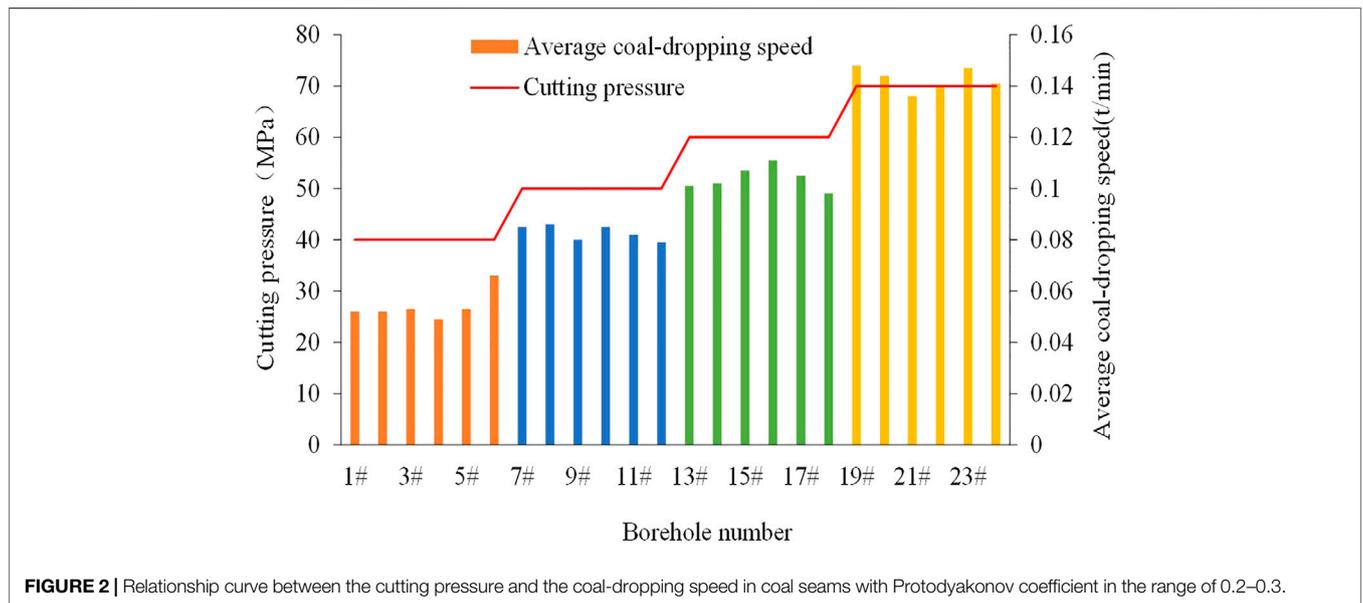


FIGURE 2 | Relationship curve between the cutting pressure and the coal-dropping speed in coal seams with Protodyakonov coefficient in the range of 0.2–0.3.

by selecting four mines with different Protodyakonov coefficients of coal seams. The basic conditions of the mines are displayed in **Table 1**.

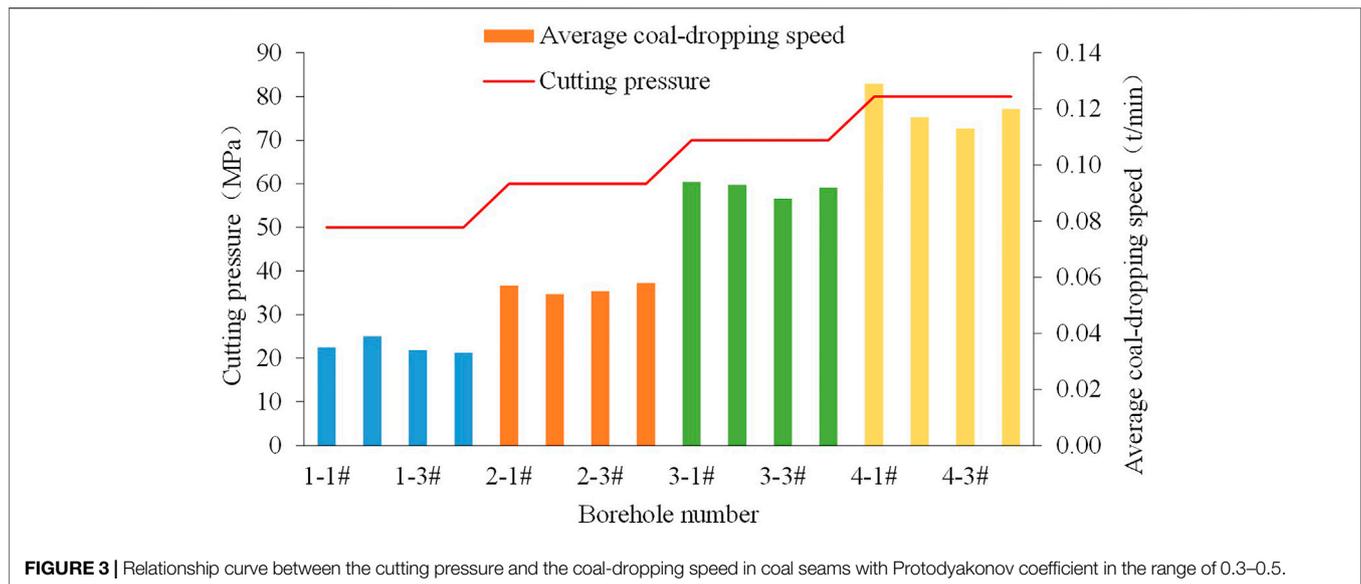
The ultra-high pressure hydraulic cutting test was conducted in the following four mines and the test results were described as follows:

The Ultra-High Pressure Hydraulic Cutting Test on Xuehu Coal Mine

Xuehu Coal Mine, located in the north of Yongcheng, Henan Province, China, is subordinated to Xuehu village in Yongcheng city. The 2-2[#] coal seam in Xuehu Coal Mine is taken as the main working coal seam. The coal seams in the coalfield occur steadily, with the thickness of 0–4.77 m, average thickness of 2.23 m, gas content within 4.6–16.2 m³/t and gas permeability coefficient of 0.0861 m³/(MPa²·d). The

Protodyakonov coefficient of the 2-2[#] coal seam is in the range of 0.25–0.7 and the attenuation coefficient of gas flows within the boreholes with one hundred meters is 1.38 days⁻¹. As for the test design, four groups of boreholes, each containing six boreholes, were distributed in the end-located drainage roadway of the No. 2306 airway in the mine, with 24 boreholes for hydraulic cutting in total. The hydraulic cutting was conducted in the four groups of boreholes for hydraulic cutting by separately using the cutting pressures of 40, 50, 60 and 70 MPa, during which coal outputs within the cutting time from borehole orifices were recorded. The test results are shown in **Figure 2**.

As shown in **Figure 2**, when the cutting pressures are 40, 50, 60 and 70 MPa, the average coal-dropping speeds of the coal seams with Protodyakonov coefficient of 0.2–0.3 are 0.052, 0.081, 0.10 and 0.143 t/min, respectively.



The Ultra-High Pressure Hydraulic Cutting Test in Zhaozhuang Coal Mine

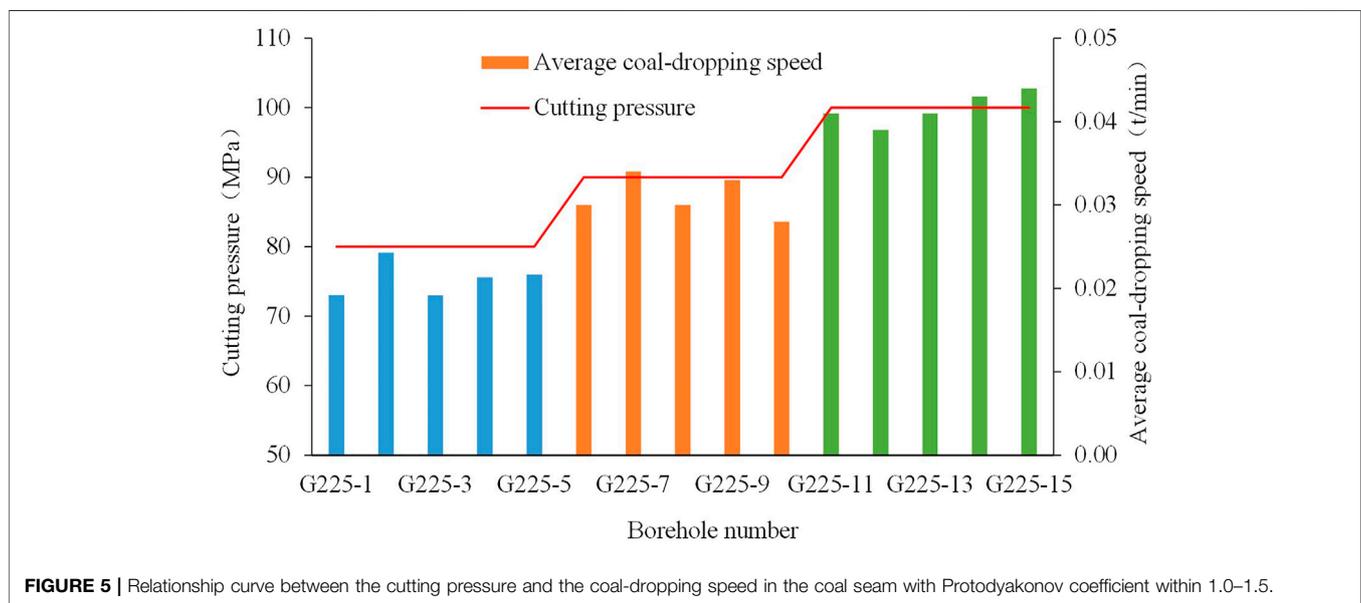
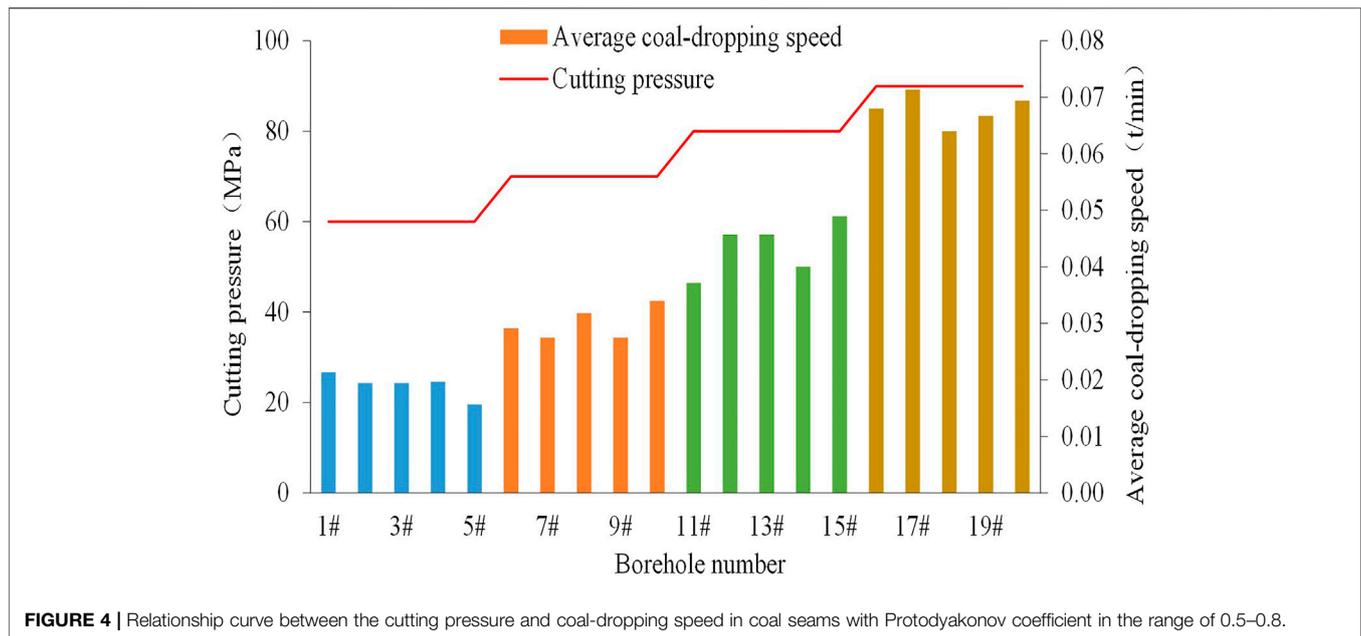
Zhaozhuang Coal Mine field is located in the southeast of Qinshui Coalfield, 53 km to the north of Jincheng City (Shanxi Province), 12 km to the north of Gaoping City, and 16 km to the south of Zhangzi County (Shanxi Province). The northern part of the coalfield is a sedimentary basin at Changzhi fault, and the middle and the southern parts correspond to the middle mountain areas eroded by Qinhe and Danhe river basins. In terms of the terrain of the areas, the altitude gradually reduces from the eastern and western parts to the middle part. To be specific, the highest point is situated in the northwest of Jubang Village at the western border, with the altitude of +1276.40 m; and the lowest point lies in the Dongdan River Valley in Guanzhai Village in the south, with the altitude of +880.70 m. It can be attained that the maximum relative altitude difference is 395.70 m. The bedrock in the southern and northern parts is mostly covered while that in middle and western parts are favorably outcropped. The coal-bearing strata in the coalfield are mainly subordinated to the Taiyuan Formation (C_3t) of the upper series of Carboniferous system and the Shanxi Formation (P_1s) of the lower series of Permian system, with shed coal scattered in the Lower Shihezi Formation and Benxi Formation. From top to bottom, Shanxi Formation contains 1[#], 2[#] and 3[#] coal seams and Taiyuan Formation contains 12 coal seams including 5[#], 6[#], 7[#], 8^{-1#}, 8^{-2#}, 9[#], 11[#], 12[#], 13[#], 14[#], 15[#] and 16[#]. The cumulative total thickness of Shanxi Formation and Taiyuan Formation is in the range of 118.19–206.86 m, generally showing the thickness of 153.57 m. The two formations involve 15 coal seams, with the total thickness of 3.38–18.21 m, the average thickness of 12.80 m and the coal-bearing coefficient of 8.33%.

The average thickness of the 3[#] coal seam in Zhaozhuang Coal Mine in the whole area is 4.69 m, with Protodyakonov coefficient in the range of 0.3–0.5. Four groups of boreholes were constructed in the airway in the north of Zhaozhuang Coal

Mine, each of which contained four boreholes, showing 16 boreholes in total. The cutting test was carried out on four groups of boreholes by separately applying the cutting pressure of 50, 60, 70 and 80 MPa. The test results are shown in **Figure 3**. Under the cutting pressures of 50, 60, 70 and 80 MPa, the average coal-dropping speeds of the coal seams with Protodyakonov coefficient within 0.3–0.5 were 0.040, 0.056, 0.092 and 0.119 t/min, respectively.

The Ultra-High Pressure Hydraulic Cutting Test in Yuwu Coal Mine

The 3[#] coal seam in Yuwu Coal Mine of Lu'an Chemical Group Co., Ltd. is located in the middle and lower part of Shanxi Formation of the lower series of Permian system. The coal seam with a large thickness is stable and recoverable in the whole area, which is 24.00–42.00 m (with an average of 33.00 m) away from K8 sandstone above and 50.48–73.12 m (with an average of 62.00 m) away from the 9[#] coal seam below. The coal seam shows the thickness in the range of 5–7.25 m, with the average thickness of 5.99 m and Protodyakonov coefficient of 0.5–0.8. The ultra-high pressure hydraulic cutting test was performed in the N1103 belt conveyor roadway (with the designed total length of about 2,068 m), with coal on the north, the N1103 working face (unmined) on the west, N1105 belt conveyor roadway (being excavated) on the east and connected to the 1[#] ventilation roadway (excavated) in the west wing of the northern air shaft on the south. The N1103 belt conveyor roadway was excavated along the roof of the 3[#] coal seam with the thickness of 6 m. In the excavation direction of the roadway, the dip angle of the 3[#] coal seam was in the range of +3° ~ -2°, showing the average dip angle of 1°. The N1103 belt conveyor roadway appeared as a rectangular cross section with the width of 5.4 m and height of 3.8 m, which was supported by using anchor nets and then strengthened with anchor cables. The N1103 belt



conveyor roadway was pre-drained by drilling long boreholes with the length of 135 m, dip angle of 1°, azimuth of 270° and spacing of 4.0 m along coal seams. In the N1103 belt conveyor roadway in Yuwu Coal Mine, four groups of boreholes were distributed along the seams, each of which five boreholes were drilled, with 20 test boreholes in total. The cutting test was conducted on the boreholes under the cutting pressures of 60, 70, 80 and 90 MPa, respectively. The test results are shown in **Figure 4**.

It can be seen from **Figure 4** that under the cutting pressures of 60, 70, 80 and 90 MPa, the average coal-dropping speeds in coal

seams with Protodyakonov coefficient of 0.5–0.8 were 0.019, 0.030, 0.044 and 0.068 t/min, respectively.

The Ultra-High Pressure Hydraulic Cutting Test in Zhaogu No. 2 mine

The main working coal seam 2-1[#] in Zhaogu No. 2 mine delivered the thickness of 4.73–6.77 m, with the average thickness of 6.16 m and Protodyakonov coefficient in the range of 1.0–1.5. Three groups of boreholes were designed in the belt roadway in the west of the mine, in which five boreholes were distributed in each group, amounting to 15 test boreholes. The cutting test was

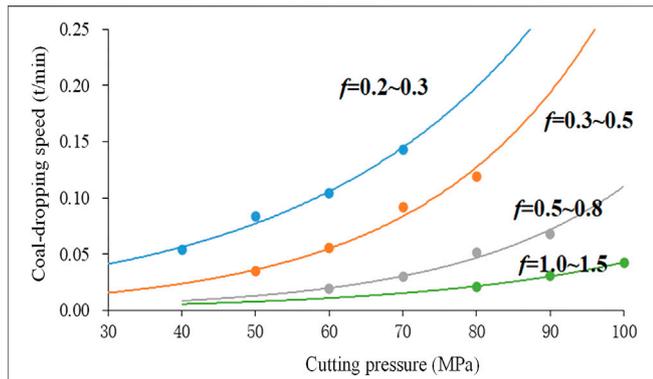


FIGURE 6 | The change curve between the jet pressure and the coal-dropping speed.

performed in the boreholes under the cutting pressures of 80, 90 and 100 MPa. **Figure 5** shows the test results.

As shown in **Figure 5**, the average coal-dropping speeds in the coal seam with Protodyakonov coefficient within 1.0–1.5 were 0.021, 0.031 and 0.042 t/min under the cutting pressures of 80, 90 and 100 MPa, respectively.

Through the above field tests, the changes of the coal-dropping speed in the coal seams with different Protodyakonov coefficients under different cutting pressures can be summarized, as shown in **Table 2**.

By fitting the above data according to the negative exponent curve, the change curves between the jet pressure and the coal-dropping speed in coal seams with different Protodyakonov coefficients can be attained, as shown in **Figure 6**.

As shown in **Figure 6**, the larger the cutting pressure is, the larger the coal-dropping speed during hydraulic cutting; moreover, with the growth of the cutting pressure, the coal-dropping speed during hydraulic cutting exponentially rises. Therefore, during high pressure cutting, the coal output dramatically increases due to the growth of the cutting pressure, thus leading to the borehole jamming and borehole outburst. The determination of a reasonable cutting pressure decisively influences the hydraulic cutting technology.

PRESSURE SELECTION FOR COORDINATED SLAG DISPOSAL DURING HYDRAULIC CUTTING

Critical Flow Velocity at the Moving Laminar Flow Regime

According to the mechanical analysis on coal particles in *Relationship Between Cutting Pressure and Coal-Dropping Speed*, it can be seen that coal particles are mainly subjected to the uplift force of fluids, effective gravity of particles and the drag force of fluids. The drag force of fluids drives coal particles to move forward while the effective gravity and the uplift force of fluids are forces with contrary directions in the vertical direction.

Therefore, the critical flow velocity V_{\min} at the moving laminar flow regime when coal particles are transformed from the rolling state to the sliding state needs to satisfy the following condition:

$$F_D - \mu F_g = 0 \quad (11)$$

where, F_g , F_d and μ separately refer to the effective gravity, the drag force of fluids and the friction coefficient between coal particles and the pipe wall.

Thus,

$$(u_w - w_s)^2 \propto \frac{4}{3C_D} \times \frac{\rho_s - \rho_w}{\rho_w} \times \frac{d_s}{D} \times \mu g D \quad (12)$$

where, g denotes the gravitational acceleration and P_s and P_w refer to the densities of coal particles and water; D stands for the equivalent diameter of the annular pipes ($D = \sqrt{R^2 - r^2}$); R and r represent the diameters of the boreholes and drill pipes, respectively; d_s denotes the average diameter of coal particles; U_s and U_w separately stand for flow velocities of coal particles and water and C_D refers to the drag force coefficient of fluids.

The drag force coefficient of coal particles can be determined according to the following equation:

$$C_D = \frac{4gd_s(S-1)}{3v_t^2} \quad (13)$$

where, v_t denotes the deposition velocity (m/s) of coal particles; $S = \rho_s/\rho_w$ refers to the density ratio of the transported particles to the carrying liquids.

Therefore, **Eq. 12** can be transformed as follows:

$$(u_w - w_s) \propto \sqrt{2gD(S-1)} \cdot \left(\frac{d_s}{D}\right)^{0.5} \quad (14)$$

Owing to $(u_w - w_s) \propto V_{\min}$ and the critical flow velocity of coal particles transformed from the rolling state to the sliding state is related to the volume concentration of particles, particle size and borehole diameter, **Eq. 15** can be attained.

$$\begin{cases} V_{\min} \propto \left(\frac{d_s}{D}\right)^{0.25} \\ V_{\min} \propto C_V^{0.2} \end{cases} \quad (15)$$

Thus, the critical flow velocity at the moving laminar flow regime can be obtained by using the dimensional analysis.

$$V_{\min} = a \sqrt{2gD(S-1)} \cdot \left(\frac{d_s}{D}\right)^{0.75} C_V^{0.2} \quad (16)$$

where, a stands for the comprehensive factor for characterizing the shape factors of coal particles.

Critical Relationship Between the Flow Rate and the slag-Disposal Capacity

To calculate the numerical relationship between the flow rate and the slag-disposal capacity, the dimensionless analysis is employed to solve **Eq. 16**. The annular solid-liquid two-phase flow model for coal particles and water is solved according to **Eq. 16** based on

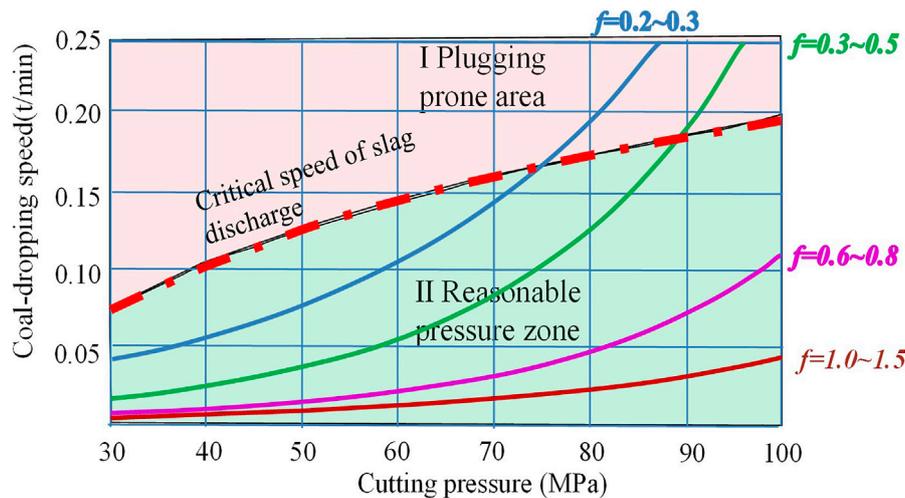


FIGURE 7 | Model for the coordinated slag disposal during the cutting.

various parameters. To be specific, R and r are 0.113 m and 0.073 m and thus $D = 0.086$ m; d_s and S equal 0.001 m and 1.42. By substituting them into Eq. 16, it can be attained that:

$$V_{\min} = 2.97 \times 10^{-2} a C_V^{0.2} \tag{17}$$

By substituting $V_{\min} = 4Q/(\pi D^2)$ and $C_V = v_s(v_s + v_w)^{-1}$ into the above equation, it is obtained that:

$$Q = 1.72 \times 10^{-4} a \cdot \left(\frac{v_s}{v_s + v_w} \right)^{0.2} \tag{18}$$

where, v_p and v_f separately denote the volumes of coal particles and liquid, respectively.

By substituting $v_s = T_0 \rho_s^{-1}$ and $v_w = Q \rho_w^{-1}$ into Eq. 18, it can be attained that:

$$T_0 = \frac{1.42 Q^6 \times 10^{19}}{1.51 a^5 - Q^5 \times 10^{19}} \tag{19}$$

By substituting Eq. 3 into Equation (23), it can be obtained that:

$$T_0 = \frac{1.8 P^3 \times 10^{-5}}{1.51 a^5 - 1.22 \times 10^{-1} P^{5/2}} \tag{20}$$

Through the above calculation, the relationship between the cutting pressure and the critical slag disposal amount is obtained.

Model for the Coordinated slag Disposal During Hydraulic Cutting

By substituting Eq. 20 into Figure 7, the model for the coordinated slag disposal during the cutting can be attained, as shown in Figure 7.

Through analysis according to the results of theoretical calculation and the field data, it is found that by taking the critical curve for the slag disposal as the boundary, zone I is the position where the borehole jamming is likely to occur. When the

selected pressure corresponds to the zone I, the coal output from boreholes is quite large and exceeds the critical slag disposal amount, thus easily leading to the borehole jamming; in the case that the pressure corresponds to the zone II, the coal output is lower than the critical slag disposal amount. On this condition, it is possible to achieve the expected cutting effect and also successfully discharge coal cinders from boreholes. Therefore, when selecting the cutting parameters, it is necessary to select the cutting pressure within the zone II, thus realizing the optimal cutting effect. It can be seen from the figure that the critical pressure inducing the borehole jamming is in the range of 70–75 MPa when Protodyakonov coefficient of coal seams ranges from 0.2 to 0.3 and it is within 80–85 MPa in the case that Protodyakonov coefficient of coal seams is in the range of 0.3–0.5.

FIELD TEST

Selection of Test Schemes

The No. 2 mine in China Coal Xinji Energy Co., Ltd. (Xijin coal mine No. 2) was used as the test mine and the 220112 working face was taken as the test area, as shown in Figure 8. The 1[#] coal seam group in 2201 mining area was divided into the 1[#] upper coal seam and 1[#] coal seam, with the average thicknesses of 3.4 and 3.9 m, respectively. The 1[#] upper coal seam and 1[#] coal seam showed an average spacing of 0.9 m and a dip angle of 5°. Through measurement, the maximum gas pressure, the gas content and Protodyakonov coefficient of 1[#] coal seam were 1.65 MPa, 6.8–8.2 m³/t and 0.48, respectively. As for the borehole design, 25 horizontal test boreholes (G1 ~ G25) were distributed in the machinery roadway of the working face and 20 boreholes (D1 ~ D20) were used for comparison, showing the spacing of 10 m and borehole depth of 120 m; the spacing between the boreholes for hydraulic cutting and those for comparison was set as 20 m. The boreholes G1 ~ G5 were test boreholes for exploring the

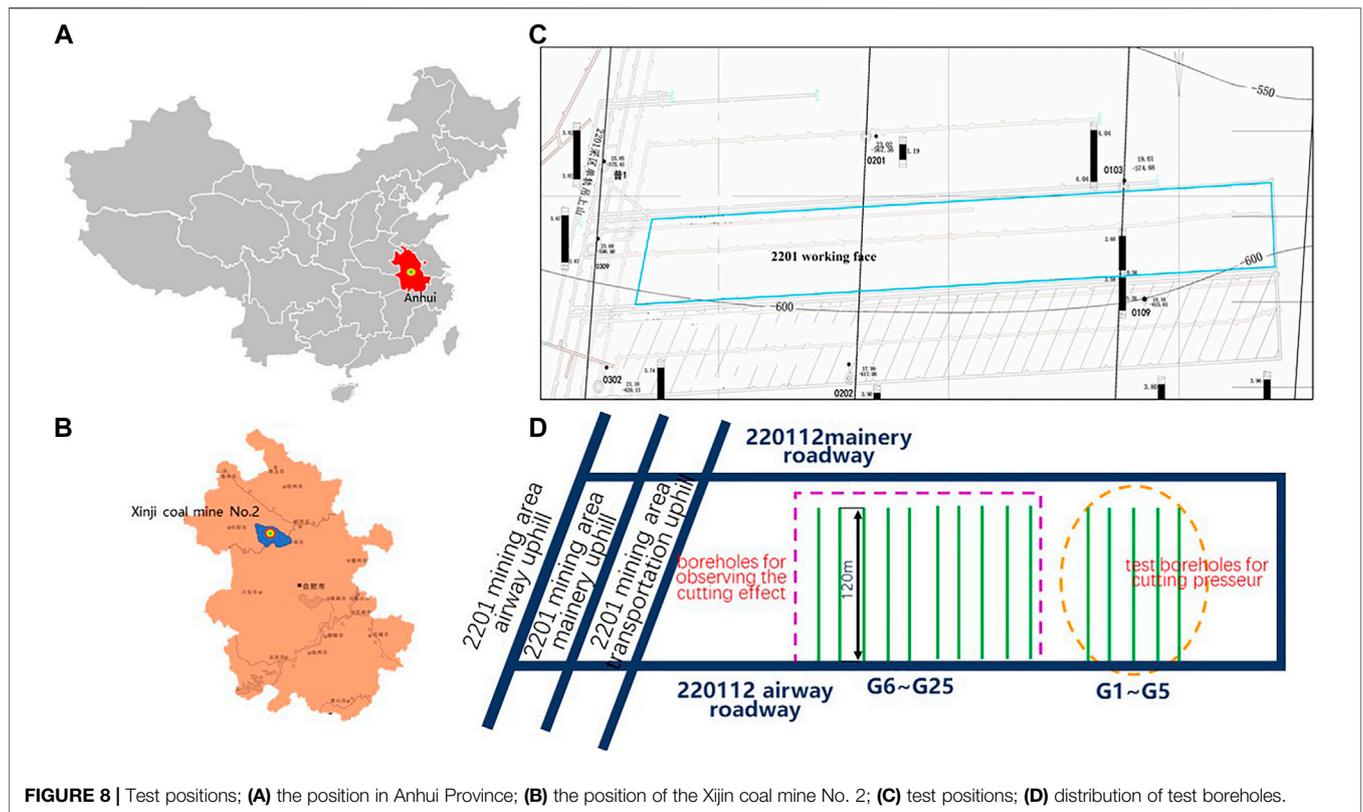


FIGURE 8 | Test positions; **(A)** the position in Anhui Province; **(B)** the position of the Xijin coal mine No. 2; **(C)** test positions; **(D)** distribution of test boreholes.

TABLE 3 | Cutting condition based on the test boreholes for the reasonable cutting pressure.

Serial number of boreholes	Protodyakonov coefficient of coal seams	Pressure/MPa	Flow rate L/min	Time/min	Coal output/t	Water- and slag-return conditions
G1	0.48	50	79	7	0.22	A small number of coal-cinder particles
G2	0.48	60	88	7	0.37	Normal water- and slag-return conditions
G3	0.48	70	97	8	0.74	Normal water- and slag-return conditions
G4	0.48	80	105	7	0.85	Borehole outburst and borehole jamming
G5	0.48	90	112	~	~	Severe borehole outburst and borehole jamming

reasonable cutting pressure. The cutting test was separately carried out under different cutting pressures, during which the cutting time, slag disposal amount and the water- and slag-return conditions were recorded. After determining the reasonable cutting pressure, the ultra-high pressure hydraulic cutting test was conducted to explore the coal output and net gas extraction; afterwards, the comparative analysis was made with those from boreholes for comparison.

Result Analysis of Test Boreholes for the Reasonable Cutting Pressure

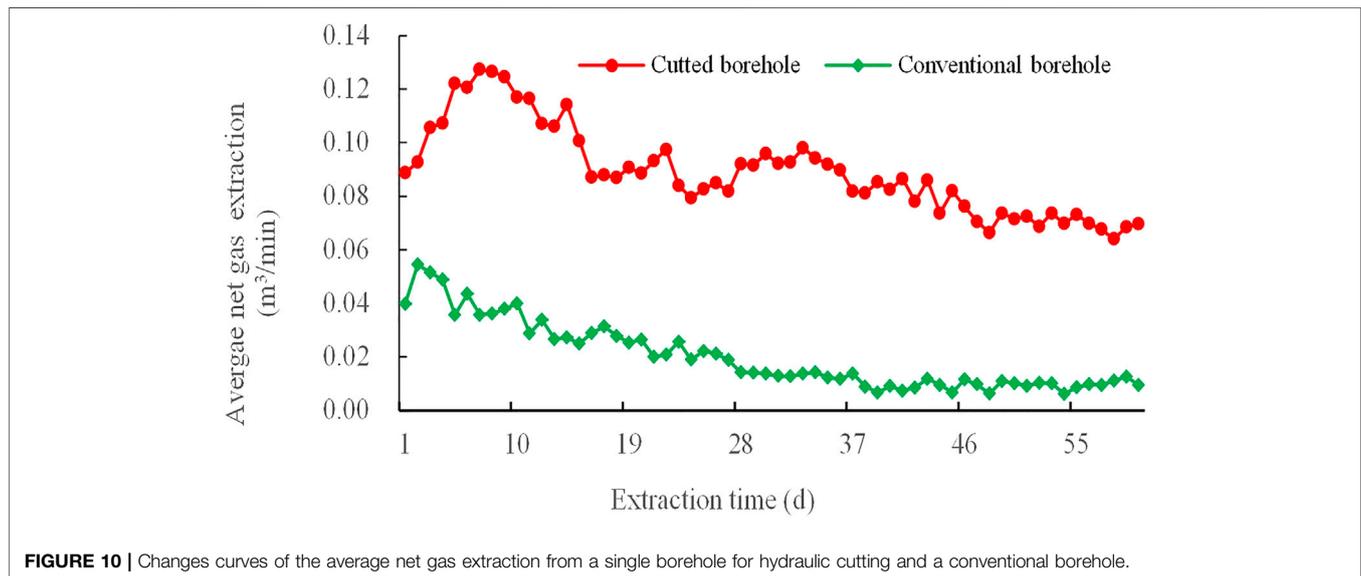
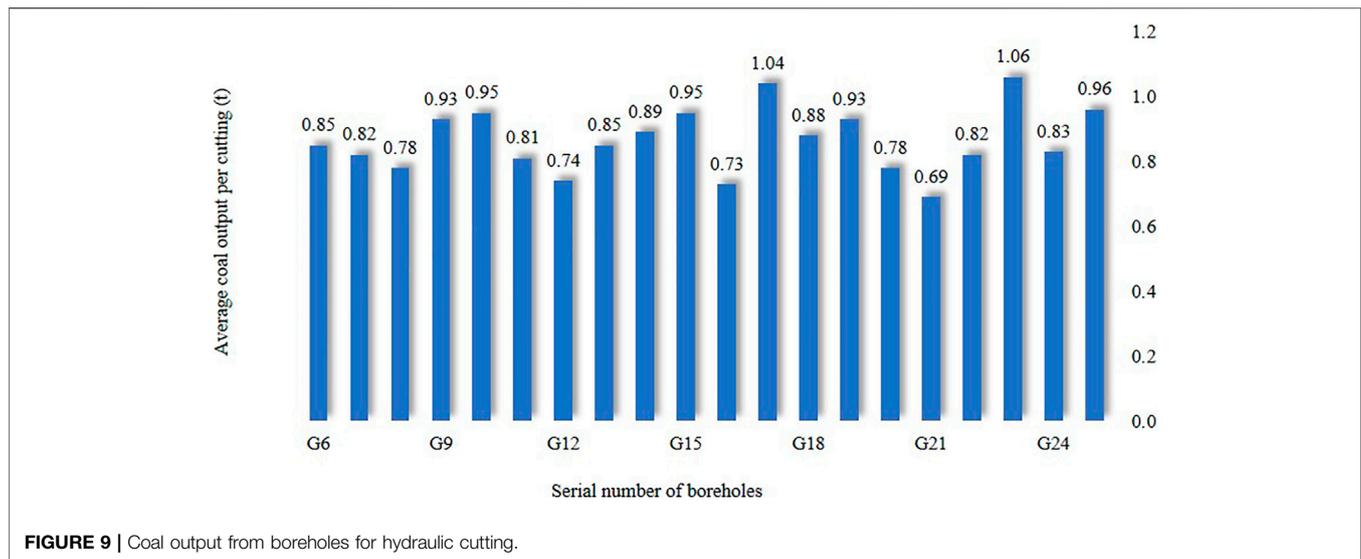
The cutting parameters and conditions obtained from the test boreholes G1 ~ G5 for the reasonable

As shown in **Table 3**, as for test boreholes G1 and G2, the coal output is low under the cutting pressure of 50–60 MPa while it significantly rises when the cutting pressure is in the range of

70–80 MPa; after the pressure grows to 90 MPa, the severe borehole jamming and borehole outburst appear in the borehole G5. It indicates that the reasonable cutting pressure should be about 80 MPa for coal seams with the Protodyakonov coefficient of about 0.48, which conforms to the result obtained according to the model for the coordinated slag disposal during hydraulic cutting.

Analysis of the Coal Output From the Boreholes for Hydraulic Cutting

Figure 9 displays the coal output from boreholes for hydraulic cutting. It can be seen from the figure that the average coal output per cutting of 20 boreholes for hydraulic cutting (G6 ~ G25) reaches the minimum of 0.69 t and the maximum of 1.06 t, with the mean value of 0.87 t. The equivalent radius is calculated as 2.15 m. During hydraulic cutting of 20 boreholes, the poor slag



disposal conditions (such as borehole jamming and borehole outburst) do not occur, which also validates the selection rationality of the cutting pressure.

min, respectively. The average net gas extraction from boreholes for hydraulic cutting is 4.5 times larger than that from conventional boreholes.

Comparative Analysis of the Gas Extraction Effect

Figure 10 shows the change curves of the average net gas extraction from a single borehole for hydraulic cutting and a conventional borehole within 60 days of extraction.

It can be seen from the figure that the maximum and minimum of the average net gas extraction from boreholes for hydraulic cutting are 0.127 and 0.064 m³/min, with the mean value of 0.089 m³/min, while those from conventional boreholes are 0.054 and 0.006 m³/min, with the mean value of 0.020 m³/

Observation on the Permeability of Coal Seams

Before performing the ultra-high pressure hydraulic cutting, the original gas permeability coefficient of 1[#] coal seam of the machinery roadway in the 220,112 working face is calculated as 0.03962 m²/MPa²·d based on the method proposed by China University of Mining and Technology. After conducting the ultra-high pressure hydraulic cutting, the gas permeability coefficient of the 1[#] coal seam is measured as 0.9905 m²/MPa²·d, which increases by 25 times than the original one.

TABLE 4 | Comparison of the effective extraction radiuses around boreholes for hydraulic cutting and conventional boreholes.

Extraction time (d)	Effective extraction radius (m) hydraulic boreholes for cutting	Effective extraction radius (m) hydraulic conventional boreholes
30	5.5	2.38
60	7.1	3.36

Comparison of the Effective Extraction Radius

The effective extraction radiuses around the boreholes for hydraulic cutting and conventional boreholes after extraction for 30 and 60 days are shown in **Table 4**. After the cutting, the impact area of the boreholes for hydraulic cutting greatly increases and the effective extraction radius is more than doubled relative to conventional boreholes.

In summary, the field tests were conducted after determining a reasonable cutting pressure. The comparison of the coal output from the boreholes for hydraulic cutting, the gas extraction effect, the permeability of coal seams, and the comparison of the effective extraction radius for hydraulic cutting was analyzed. The field test results show that the reasonable cutting pressure can ensure the safety of cutting operation and improve the extraction effect.

CONCLUSION

In this paper, a model for coordinated slag disposal during hydraulic cutting based on coal-water two-phase flow was established according to the annular solid-liquid two-phase flow theory. Besides, the model for selecting the reasonable cutting pressure was used to guide the field test. The primary conclusions are displayed as follows.

- (1) By analyzing the test data on four mines containing coal seams with different Protodyakonov coefficients obtained through the field cutting test, the relationship curves between the coal-dropping speed and the cutting pressure under different Protodyakonov coefficients were attained; moreover, it suggested that the coal-dropping speed during hydraulic cutting exponentially increases with the growth of the cutting pressure.
- (2) By constructing the annular solid-liquid two-phase flow model with coal-water mixture, the mechanical condition of coal particles at different motion stages was analyzed. The result showed that the concentration and flow velocity of coal-water two-phase flow are main factors influencing the slag disposal from boreholes; the critical flow velocity at the moving laminar flow regime is considered as that for the coordinated slag disposal from boreholes.
- (3) Through mechanical analysis of the moving laminar flow regime of coal-cinder particles, the critical flow velocity at the moving laminar flow regime was obtained. In addition, the model for selecting the reasonable cutting pressure based on the coordinated slag disposal theory was established according to

the curve relationship with the coal-dropping speed, which guided the cutting test on the 220112 working face. When the reasonable cutting pressure during the slag disposal in the coal seam with Protodyakonov coefficient of 0.48 was determined as about 80 MPa, no borehole outburst and borehole jamming were found during the cutting of test boreholes, with the average coal output per cutting of 0.87 t and the equivalent radius of 2.15 m. The average net gas extraction from boreholes for hydraulic cutting was 4.5 times of that from conventional boreholes; additionally, relative to conventional boreholes, the gas permeability coefficient rose by 25 times and the effective extraction radius is more than doubled.

- (4) The test results showed that the model for selecting the reasonable cutting pressure based on the coordinated slag disposal theory clarified the relationships of the cutting pressure, coal-dropping speed and the critical slag disposal amount. It can ensure the safety of the cutting operation while improving the extraction effect during hydraulic cutting, which effectively guides the selection of the cutting pressure in field tests.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

The authors have made a significant contribution to the manuscript. YZ was responsible for the framework design and writing of the paper, FJ was responsible for the theoretical analysis in the manuscript and QZ was responsible for the revision of the manuscript.

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