

Article

The Enhancement of Lump Coal Percentage by High-Pressure Pulsed Hydraulic Fracturing for Sustainable Development of Coal Mines

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Abstract: The enhancement of lump coal percentage (LCP) is of great significance for most aging mines to achieve the production reduction and quality improvement. In order to enhance the LCP of hard coal seam in fully mechanized mining face and prolong the service life of aging mines, this paper puts forward the technological path of LCP enhancement using high-pressure pulsed hydraulic fracturing (HPPHF) based on the detailed analysis of the main factors controlling LCP. By analyzing the correlation between coal fracturing and LCP, the enhancement mechanism of LCP through HPPHF was concluded. Using the extended finite element method, a fluid–solid coupling numerical model of high-pressure pulsed water injection into coal seam was established, and effects of the fracturing method, pulse amplitude, pulse frequency, and water injection pressure on fracturing performance were assessed. Simulation results demonstrate that HPPHF can effectively reduce the required maximum pressure in fracturing, thus providing a higher percentage of coal lumps with lower energy consumption through the repeated pulsed loading of coal masses. Variations in pulsed pressure amplitude and frequency, as well as water injection pressure were positively correlated with fracturing performance. By their effect on the fracturing performance, we found that water injection pressure had the greatest influence, and the pulse amplitude and frequency had similar effects. At the same time, “high amplitude-high frequency” and “high amplitude-low frequency” had characteristics of short initiation time, large initiation pressure, but small fracture width, while “low amplitude-high frequency” and “low amplitude-low frequency” had characteristics of slow initiation speed, low initiation pressure, but large fracture width. Through the field test results in the fully mechanized mining face of Shichangwan Coal Mine, it was found that LCP with a diameter range of 13–100 mm was significantly enhanced by HPPHF. The present study is considered quite instrumental in providing a theoretical foundation for enhancing the LCP of hard coal seams and the sustainable development of coal mine enterprises.

Keywords: high-pressure pulsed hydraulic fracturing; lump coal percentage; pulse parameters; fluid-solid coupling; sustainable development

1. Introduction

With an increasing share of fully-mechanized mining in global coal production, the advanced mining equipment resolves more and more challenging tasks in coal face mining. Although it ensures a higher yield and efficiency of mining, as well as significantly reduces the labor intensity, it also results in a steady drop in the large lump coal recovery ratio. Low lump coal percentage (LCP) not only increases

the specific energy consumption of mining but also results in a decline in the coal price, thereby causing enormous loss of mine's economic benefits [1–4]. Meanwhile, a large amount of dust is produced in the working, which increases the hazards related to the coal dust-explosion and jeopardizes the miners' physical health by triggering the pneumoconiosis disease [5–7]. With the increase of aging mines year by year, prolonging the service life of aging mines has become a major practical problem, and the enhancement of per ton coal benefits becomes particularly important. The increase of LCP appears as the first choice in many aging mines for production reduction and quality improvement, which is of great significance for the sustainable development of aging mines. Therefore, the particular way to enhance LCP of hard coal seams in fully-mechanized mining faces becomes a challenging problem that must be urgently and comprehensively addressed in each coal mine.

Scholars all over the world have conducted a great deal of research on the enhancement of LCP and achieved some impressive results. Hurt et al. conducted coal rock cutting tests and reported that LCP could be enhanced by changing the shape of the shearer's cutting head, cutting speed, and depth [8]. Liu et al. achieved the enhancement of LCP by changing the shearer's pulling speed and the roller's rotating speed [9]. Wu et al. adopted the loose pre-fracturing millisecond blasting to alleviate the coal fragmentation, in combination with parallel transferring without a drop, and spiral coal bunker for buffered coal slip, LCP was effectively enhanced [10]. Currently, most studies regarding the enhancement of LCP are focused on the improvement of shearer structure and cutting way, and transforming the transferring system, while field application performances receive much less attention. The implementation of innovative technological methods is very topical. In particular, the high-pressure pulsed hydraulic fracturing (HPPHF) is a novel coal seam fracturing technique that was inspired by ordinary hydraulic fracturing. Specifically, a certain amount of pulsed water with a particular frequency is continuously injected into the borehole. After the application of pulsed wave cycles with the maximal and minimal pressure peaks, the alternating or repeated load is applied to the cracks formed in the coal, which enhances their propagation and eventually to the fatigue failure of the coal rock masses [11–13]. HPPHF can generate new cracks in the coal seam via pre-fracturing to achieve the goal of LCP enhancement. At present, HPPHF has been applied for the pressure relief and permeability improvement in coal seams but, to the best of our knowledge, it has not been applied to enhancing LCP of hard coal seams yet [14,15]. Therefore, the theoretical analysis of LCP enhancement in hard coal seams employing HPPHF is quite expedient.

In this paper, we investigated the case study of Shichangwan Coal Mine with a low LCP, analyzed the correlation between coal pre-fracturing and LCP, and propose the technological path of enhancing LCP using HPPHF. By constructing the fluid–solid coupling model of HPPHF, the difference between pulsed and static fracturing was compared, and the effects of pulse amplitude, pulse frequency, and water injection pressure on the fracturing performance were discussed in depth. Finally, industrial tests were performed for validating the feasibility of HPPHF in enhancing LCP of a hard coal seam. The present study adds to the theoretical justification efforts for enhancing the LCP of hard coal seams and the sustainable development of coal mine enterprises.

2. Engineering Background

2.1. Mining Geological Conditions

Shichangwan Coal Mine is located in Nlindohai Town, Yijinhuluo County, Ordos City, Inner Mongolia Autonomous Region, China. The mine has a simple geological structure, and the coal seam has a burial depth of 95–119 m and an inclination angle of 1–3°. Currently, the reserves of the mineral coal seam in the mine are less than 2 million tons. In particular, V-1 and V-2 coal seams are residual mining coal seams, with the thickness of 1.23 m and 1.80 m, respectively, which fall into the category of thin and moderately-thick coal seams. Figure 1 displays the profile histogram of the boreholes in the coal seam.

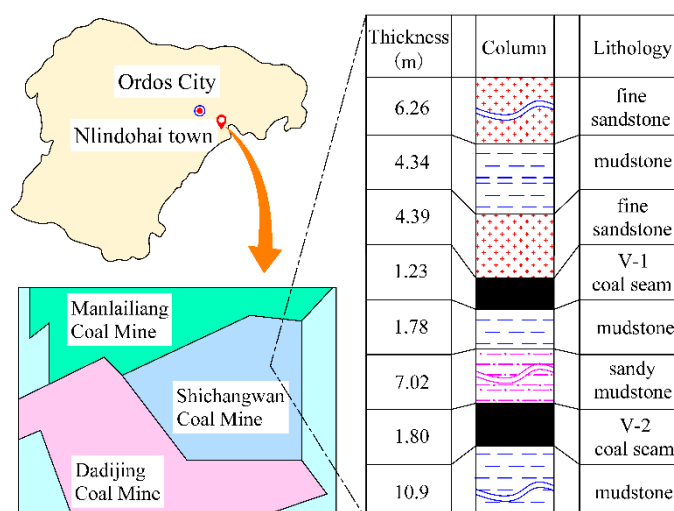


Figure 1. Profile histogram of the borehole in the coal seam.

For prolonging the mine service life, coal production should be reduced while coal resource quality should be urgently improved. At present, LCP of the mine's coal seam is only 11–12%. Given the coal price on the local market, the lump coal cost is up to 400 yuan/ton (i.e., ~58 USD/ton), while that of pulverized coal is only 270 yuan/ton (i.e., ~40 USD/ton). Thus, the price of lump coal is higher than that of pulverized one by 33%. Therefore, Shichangwan Coal Mine urgently needs to enhance the LCP and increase the per ton coal price. For this reason, the coal mine has adopted such methods as changing the shape of the shearer cutting head and optimizing the underground coal transportation route, but the application effect is not very good. Therefore, Shichangwan Coal Mine needs other feasible methods to enhance the LCP.

2.2. Analysis of Main Controlling Factors of LCP

By combining practical production condition in Shichangwan Coal Mine and coal's physical and mechanical measurement results, the main reasons that account for low LCP in Shichangwan Coal Mine can be concluded below. Firstly, due to considerable hardness, coal is not easily peeled off during the cutting process by the shearer, thereby producing a large amount of pulverized coal. Secondly, the coal seam under mining is thin, and the designed parameters of the shearer do not match the thickness of the coal seam (i.e., the shearer drum has a large diameter and is equipped with numerous blades); accordingly, thin- and moderate-thickness coal seams are fully cut by the shearer. Finally, during coal transportation process, a significant amount of lump coal can be broken into pulverized coal after repeated impacts and friction, as well as secondary coal fragmentation.

According to the above analysis, the coal structure, coal mining devices, and transportation level influence the coal seam's LCP. Enhancing LCP should start from the production source of lump coal, i.e., coal structure should first be changed. Figure 2 displays the experimental results of joint fractures in V-2 coal seam of Shichangwan Coal Mine. It can be readily observed that the fractures in the coal seam are mainly shrinkage microfractures with no obvious fracture development. Meanwhile, according to mechanical measurement results, the hardness factor of the V-2 coal seam was up to 2.6, i.e., V-2 coal seam can be regarded as a moderately-hard coal seam. Therefore, increasing the fractures in the coal seam and changing the coal intensity will enhance the LCP of Shichangwan Coal Mine.

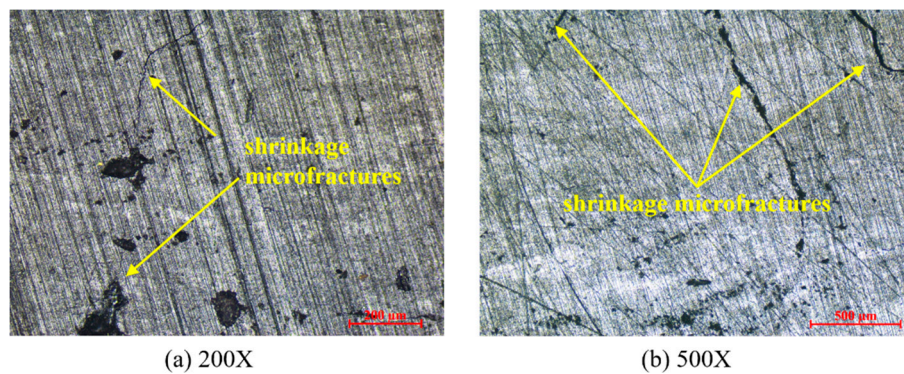


Figure 2. Experimental results of joint fractures in V-2 coal seam.

3. Mechanism of LCP Enhancement via HPPHF

3.1. HPPHF Mechanism

Using HPPHF, a pulsed high-pressure pump is used for generating pulsed water pressure, and then, the generated pulse wave is transmitted to coal via water's energy transferring operation to crack the coal and promote the fracture propagation in it [16,17]. The whole process can be subdivided into two stages. First, the high-pressure flow gets into the coal seam and promotes the interconnection of pre-existing fractures; meanwhile, because of the expansion stress of high-pressure water on the fractural wall in the coal seam, the fracture surfaces are expanded and extended to form new fractures. Second, the high-pressure pump can provide continuous and periodic expansion stress, which can impose lasting impacts on the coal and generate fatigue failures. Next, secondary fractures are gradually formed and extended, and interconnected fracture network is finally established, to achieve the coal fracturing.

The biggest difference between HPPHF and conventional hydraulic fracturing is that pulsed hydraulic fracturing produces continuous pulse stress waves, and the pulsed load is repeated on the coal and rock mass, thereby causing greater damage with less energy. The dynamic effects of pulse waves are studied below.

When considering coal and rock mass as ideal elastic body [18,19], the results of elastic theory can be directly used to study the propagation of pulse stress wave, which conforms to the generalized Hooke's law. Because the pulse stress wave produced by pulsed pump is sinusoidal, its stress can be expressed as follows:

$$\sigma_0 = A_0 \sin\left[f\left(t - \frac{x}{c}\right) + \varphi\right] \quad (1)$$

where A_0 , f , c , x , φ are the amplitude, frequency, wave velocity, distance from the starting point, and initial phase of the sine wave, respectively.

When the fluctuating water stress wave is transmitted to the interface of water and coal at the fracture, one part of the stress wave will be reflected back from the interface, the other part of the stress wave will produce the spherical wave propagating to the coal body with the impact point as the spherical center and enter the coal body through the interface. The incident wave and the reflected wave form a superposition, and the superposition stress can be expressed as follows:

$$\sigma(x, t) = \sigma_I(x, t) + \sigma_R(x, t) = \sigma_0 \sin\left[f\left(t - \frac{x}{c}\right)\right] - V\sigma_0 \sin\left[f\left(t - \frac{2L - x}{c}\right)\right] \quad (2)$$

where V is the reflection coefficient and L is the length from the free surface.

It can be seen from the above equation that the stress wave's magnitude after superposition depends on σ_0 and V , where σ_0 depends on A_0 , f , c , φ . In this way, stress in some places is increased, and stress is removed at some positions, so that a small pump pressure will generate a local large stress wave pressure, thereby aggravating the damage of the coal and rock mass.

3.2. Correlation between Coal Pre-Fracturing and LCP

Coal structure is a dominant factor that controls LCP during the coal mining process. The relevant indices of coal structure mainly include coal hardness degree, fractures, and the development degree of damages [20]. As shown in Figure 3, when the coal mass containing a significant number of pores and fractures is subjected to the external force by the shearer's cutting teeth of, high stresses are concentrated in the vicinity of cracks, especially near the crack tips. When the elastic energy generated by the stress concentration is converted into the resistance work required for the development of cracks, the coal mass will be cracked along the fracture sources, thereby producing lump coal after the coal fracture. As compared to original coal, coal with more developed fractures is more easily damaged under same external force. Therefore, in hard coal seams, lump coal is easily formed during the mining of coal with more developed fractures. However, hard coal with fewer fractures is more inferior in cuttability, and a significant amount of pulverized coal can only be produced under the external force applied by the cutting teeth of the shearer.

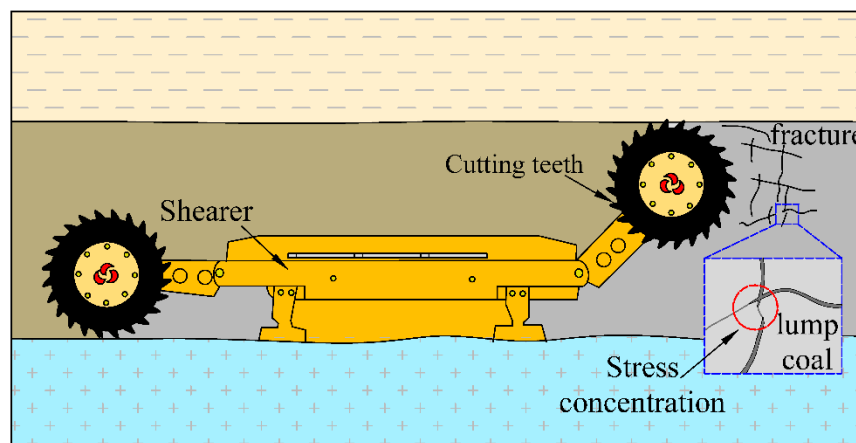


Figure 3. Coal cutting process by the shearer.

The application of HPPHF can reduce coal hardness, increase the development degree of fractures in coal, and improve coal's cuttability, which can thus enhance LCP in coal mining. This study aims to use HPPHF for the enhancement of LCP in the fully-mechanized mining face.

4. Effects of HPPHF Parameters on Coal Fracturing

4.1. Elaboration of the Numerical Model

4.1.1. Simulation Method

Injection of high-pressure pulsed water into the coal seam is a dynamic coupling process of water seepage and coal deformation. Since hydraulic pressure at the fracture surface exhibits a dynamic variation with the propagation of fractures during the dynamic fracturing process, one cannot directly simulate the hydraulic fracturing process and, instead, should conduct the secondary development. In this study, coal fracturing and the propagation of fractures in the coal were simulated utilizing the extended finite element method, and the Soil module in ABAQUS was employed for simulating the solid–fluid coupling process of fracture initiation and propagation after the injection of high-pressure water injection.

The extended finite element method was to represent the discontinuity of the displacement field by introducing the enrichment function with discontinuous properties in the traditional finite element displacement interpolation function, which usually includes a fracture tip progressive displacement

function that captures the singular points around the fracture tip, and the jump function to represent the displacement jump on the fracture surface, the expressions are as follows:

$$u = \sum_{I=1}^N N_I(x) \left[u_I + H(x) a_I + \sum_{\alpha=1}^4 F_{\alpha}(x) b_I^{\alpha} \right] \quad (3)$$

where $N_I(x)$ refers to conventional shape function, u_I refers to displacement vector of continuous part in finite element solution, a_I refers to fracturing unit node expansion degree of freedom, $H(x)$ refers to jump function, b_I^{α} refers to fracture tip node expansion degree of freedom, $F_{\alpha}(x)$ refers to fracture tip progressive displacement function, and I refers to node set for all nodes in the grid.

When the fracture is simulated by XFEM, the fracture surface does not need to coincide with the element boundary, and the fracture can be expanded in the element. Because the description of the fracture surface is completely independent of the mesh, the fracture does not need to be reconstructed along any path, greatly reducing the amount of computation.

Currently, scholars mainly adopt (i) the maximum principal stress, (ii) the maximum principal strain, and (iii) the secondary stress criteria for assessing the stress–strain conditions of the fracture initiation via the extended finite element analysis [21,22]. Numerous numerical simulation results obtained by several researchers strongly suggest that the maximum principal stress criterion applies to the fracture initiation in HPPHF numerical simulations. It was used in this study as follows: as soon as the hydraulic stress exceeds the critical maximum principal stress, damages appear, and coal is fractured. The maximum principal stress criterion can be expressed as follows:

$$f = \left\{ \frac{\langle \sigma_{\max} \rangle}{\sigma_{\max c}} \right\} \quad (4)$$

where $\sigma_{\max c}$ is the critical maximum principal stress of the coal mass. $\langle \sigma_{\max} \rangle$ is equal to the absolute value of $\sigma_{\max}$ when it is positive, and $\langle \sigma_{\max} \rangle$ is equal to zero when $\sigma_{\max}$ attains zero or negative values.

The propagation of cracks during hydraulic fracturing is a complicated process, and the type of formed cracks cannot be determined before the deformation process has started. The crack propagation after pre-fracturing can be estimated via the B-K criterion proposed by Benzeggagh and Knane [23].

4.1.2. Numerical Simulation

As shown in Figure 4, the numerical simulation model with a size of 20×5 m was constructed based on the geological conditions of Shichangwan Coal Mine. Since initial fractures exhibit no deviation when the fluid flows through, and the work performed by fluid pressure in initial fractures is much smaller than that in the non-fractured region, the fracturing borehole can use initial fractures for its characterization. The length of initial fractures can be used for characterizing the diameter of the fracturing borehole, i.e., $d = 100$ mm. The initial crustal stresses (i.e., stresses generated along the boundaries of tectonic plates in response to plate movement) in vertical and horizontal directions were 3.0 and 6.0 MPa, respectively, and the pore pressure in the formation was 1 MPa. Table 1 lists the basic parameters of the elaborated numerical model.

Table 1. The basic parameters of the elaborated numerical model.

	Elastic Modulus/GPa	Poisson's Ratio	Tensile Strength/MPa	Permeability Coefficient/(m/s)	Filtration Coefficient/(m/Pas)
Coal Seam	2.80	0.30	1.5	1×10^{-7}	1×10^{-13}
Roof and Floor	4.50	0.25	2.3	1×10^{-7}	1×10^{-14}

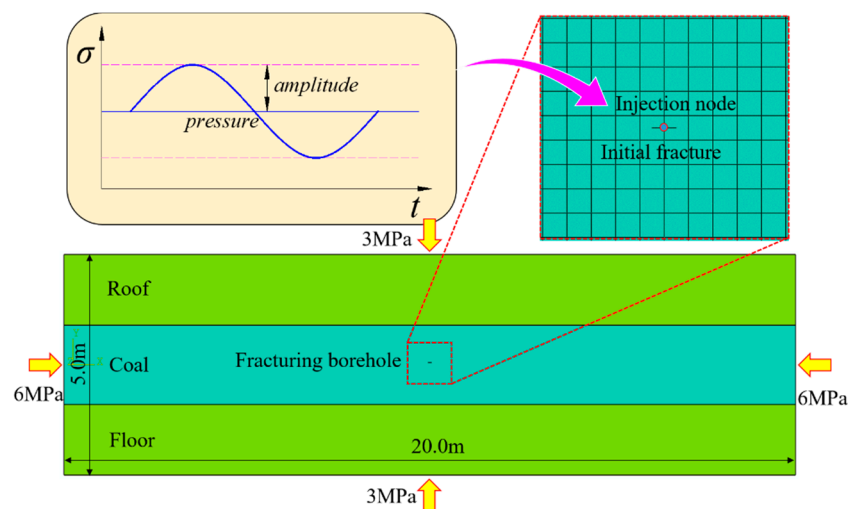


Figure 4. Elaborated numerical model.

4.2. Comparison of Pulsed and Static Fracturing Effects

Using the above numerical model, simulations were performed for comparing the fracturing effects of different fracturing methods, during which the simulation time and mean water-injection pressure were set at 100 s and 10 MPa, respectively. Pulsed hydraulic fracturing refers to injecting water with the sinusoidal pattern of pressure variation into the coal seam. The fluid pressure at a unit node near the monitoring water injection point was set as water injection pressure.

Figure 5 shows the variations of water injection pressure over time using different fracturing methods. Regarding hydraulic pressure, fracture initiation pressures for static and pulsed hydraulic fracturing methods were 13.8 and 10.9 MPa, respectively. The fracture initiation pressure using pulsed hydraulic fracturing decreased by 21% compared to that of static fracturing. Concerning fracturing time, fracture initiation instants for static and pulsed hydraulic fracturing methods were 1.8 and 2.35 s, respectively. In the case of pulsed hydraulic fracturing, fractures appeared later than under static fracturing conditions, which suggests that these two fracturing methods imply two different failure mechanisms. The mechanism of pulsed hydraulic fracturing perceives that it can impose fatigue damages to coal. Despite low pressure, coal can also be fractured at sufficient pulsed load levels.

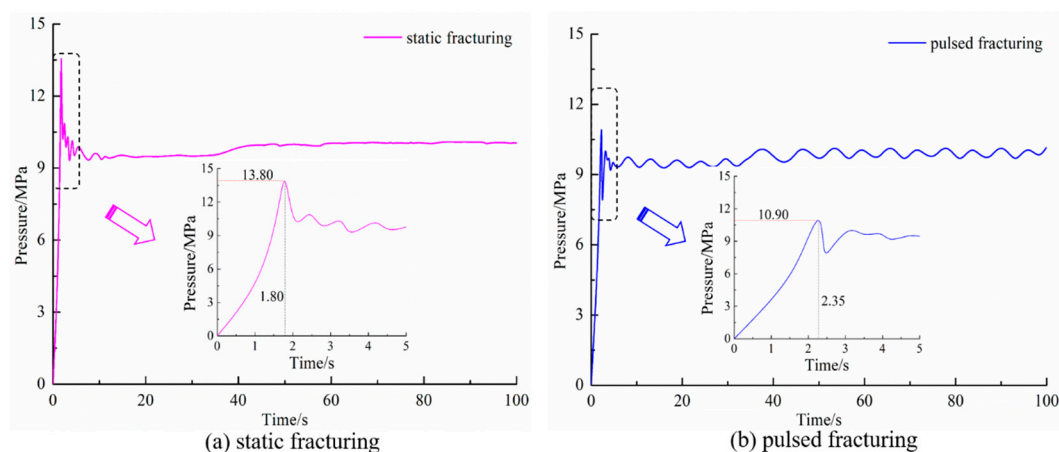


Figure 5. Variations in water-injection pressure over time when using different fracturing methods.

Fracture propagation length can directly reflect the coal fracturing performance. Figure 6 displays the fracturing performances in the same periods using different fracturing methods, in which PHILSM represents the displacement function describing the fracture surface. Within the same fracturing

periods, fracture propagation radius using the pulsed fracturing was larger than that in static fracturing, which shows that pulsed hydraulic fracturing has a better fracturing effect.

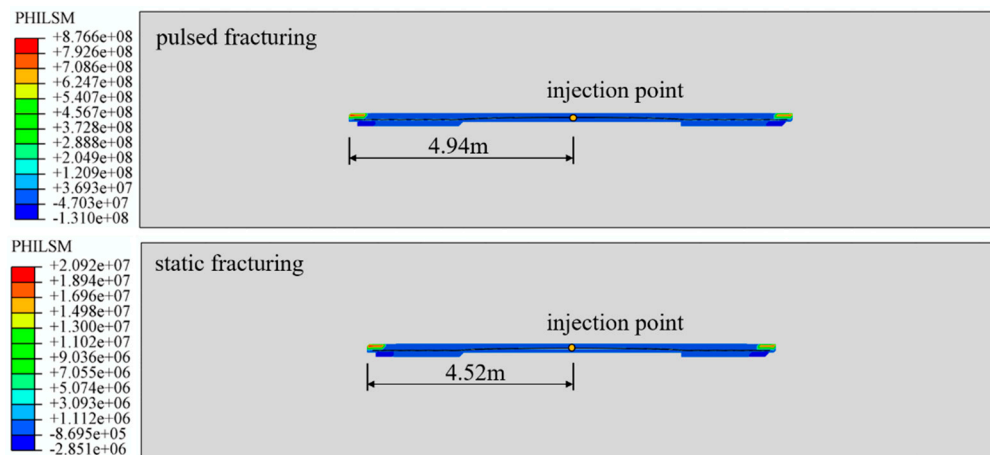


Figure 6. Comparison of fracturing effects using different fracturing methods.

Conclusively, pulsed fracturing can effectively reduce the required maximum pressure in the fracturing process and need longer fracturing time. Using pulsed hydraulic fracturing, coal can be effectively crushed by repeated pulsed loads with less energy consumption.

4.3. Effect of Pulse Amplitude on the Coal Fracturing Performance

Next we examined the impact of the variation amplitude of pulse pressure on fracturing performance when using pulsed hydraulic fracturing. The simulation results obtained for the water injection pressure and pulse frequency were fixed at 10 MPa and 10 Hz, respectively, while pulse amplitude was set at 1, 2, 3, 4, and 5 MPa (Figure 7).

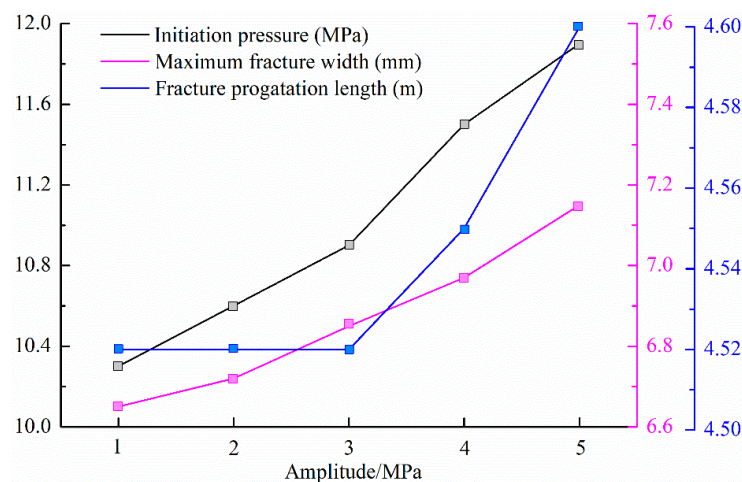


Figure 7. Fracturing characteristics under pulsed hydraulic pressure at different amplitudes.

According to the post-processing results, as pulse amplitude increased from 1 to 5 MPa, fracture initiation pressure increased from 10.5 to 11.9 MPa (i.e., by 13.3%), the maximum fracture width increased from 6.65 to 7.15 mm (by 7.52%), and fracture propagation length increased from 4.52 to 4.60 m (by 1.77%). It can, therefore, be concluded that the pulse amplitude variation can influence the fracture initiation pressure, maximum fracture width, and fracture propagation length. As the pulse amplitude increased, the generated fractures expanded both in length and width. Within a certain range, the greater the pulse amplitude, the greater the degree of fatigue damage to the coal body,

and the better the fracturing performance of the coal body. When the pulse amplitude is 1–3 MPa, the upper pressure limit of pulsating water injection is lower than the pressure at which the fracture of the coal body is further expanded. Therefore, the fracture propagation length is basically unchanged, but the fracture propagation width is slightly increased. When the amplitude is greater than 3 MPa, the upper pressure limit of pulsating water injection can cause the fracture to further expand, and thus the fracture propagation length is also increased.

4.4. Effect of Pulse Pressure Variation Frequency on the Fracturing Performance

The impact of the pulse pressure's variable frequency on the fracturing performance was also investigated in depth. Figure 8 displays the simulation results for pulsed water injection pressure and pulse amplitude fixed at 10 and 3 MPa, respectively, at the pulse frequency values of 5, 10, 15, 20, and 25 Hz.

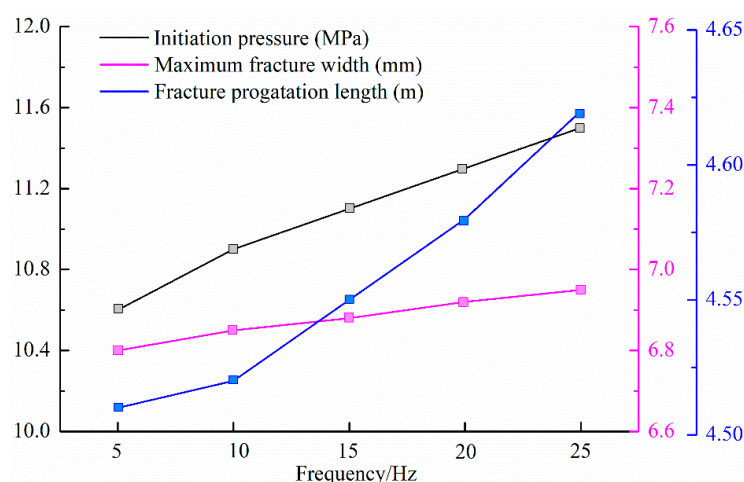


Figure 8. Fracturing characteristics at different pulsed frequencies.

The post-processing results demonstrate that, as pulse frequency increased from 5 to 25 Hz, fracture initiation pressure increased from 10.6 to 11.5 MPa (i.e., by 8.49%), the maximum fracture width increased from 6.80 to 6.95 mm (by 2.21%), and fracture propagation length increased from 4.51 to 4.62 m (by 2.44%). Pulse frequency variation can also influence the fracture initiation pressure, maximum fracture width, and fracture propagation length. At higher pulse frequencies, more extended and broad fractures are promoted. During the injection of high-pressure pulsed water into the coal seam, micro-fractures in the coal are expanded and enclosed regularly; after significant enhancement of pulse frequency, the fractures that are not entirely enclosed suffer from high-pressure water load again, which can significantly reduce the energy consumption in the water injection process. When the pulse frequency exceeds 10 Hz, the energy in the water injection process is mainly used for fracture propagation, and the energy consumption is extremely small, so that the fracturing performance is better and the fracturing efficiency is higher.

Theoretically, pulsed pressure at higher frequency variations imposes more obvious cumulative damages on coal; however, it is difficult to achieve too high pulse frequency in the actual production. There exist some limitations concerning the following two aspects. On the one hand, pneumatic frequency modulation device and reserving valve in the pulsed water injection equipment require certain reaction time for the operation. On the other hand, the rise and drop of water injection pressure in the water injection hole also takes some time. Therefore, selecting pulse frequency should also take into account the field water injection and equipment operation characteristics.

4.5. Effect of Water Injection Pressure on the Fracturing Performance

Finally, the effect of water injection pressure on coal fracturing performance was examined, with the high-pressure pulsed water injection amplitude and pulse frequency being fixed at 3 and 10 Hz, respectively, and water injection pressure set at 8, 9, 10, 11, and 12 MPa. The corresponding simulation results are depicted in Figure 9.

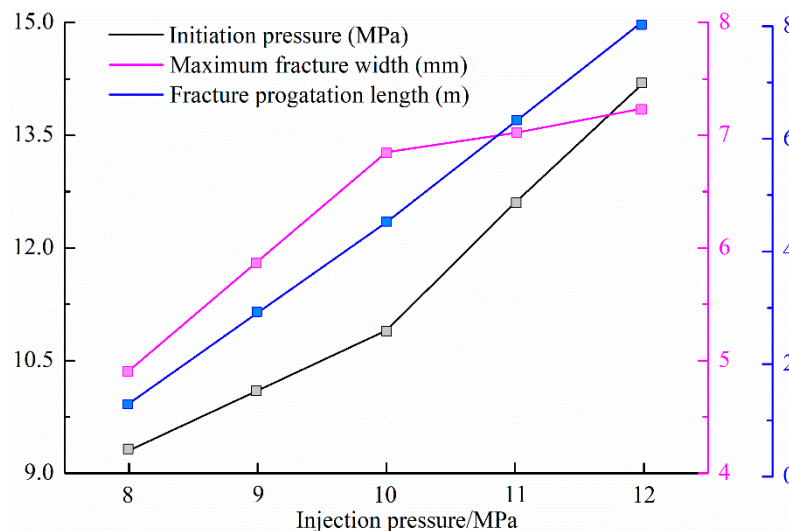


Figure 9. Fracturing characteristics under different water injection pressures.

According to the post-processing results, as water injection pressure increased from 8 to 12 MPa, fracture initiation pressure increased from 9.3 to 14.2 MPa (i.e., or by 52.69%), the maximum fracture width increased from 4.91 to 7.24 mm (by 47.45%), while the fracture propagation length increased from 1.20 to 8.12 m (by 576.67%). Thus, the water injection pressure variation imposed a more significant impact on the fracture initiation pressure, maximum fracture width, and fracture propagation length than pulse frequency and pulse amplitude. At a more substantial water injection pressure, the pressure in the fracture increased more rapidly, and the fractures extended farther in the length direction. An increase in pressure can augment the normal stress at the fracture surface, thereby increasing its width. However, the rate of increase shows a slowing trend, because when the fracture propagation width is increased to a certain extent, it takes more energy to further increase the fracture width than the fracture length.

The above results strongly indicate that pulse amplitude, pulse frequency, and water injection pressure are influencing factors that control HPPHF performance. In the decreasing order of their fracturing effect, the water injection pressure has the greatest influence, followed by the pulse amplitude and frequency, and the pulse amplitude and frequency have similar effects. In field operation, pulse amplitude and frequency changes are relatively easier and with lower cost. To further determine the optimal HPPHF parameter combination, the following simulation was carried out on the basis of the water injection pressure of 10 MPa: Scheme A, high amplitude and high frequency (amplitude is 5 MPa, frequency is 20 Hz); Scheme B, low amplitude and high frequency (amplitude is 1 MPa, frequency is 20 Hz); Scheme C, high amplitude and low frequency (amplitude is 5 MPa, frequency is 5 Hz); and Scheme D, low amplitude and low frequency (amplitude is 1 MPa, frequency is 5 Hz).

Table 2 shows the fracturing effect of different HPPHF parameter combinations. It can be seen that “high amplitude-high frequency” and “high amplitude-low frequency” have the characteristics of short initiation time, large initiation pressure, but small fracture width; while “low amplitude-high frequency” and “low amplitude-low frequency” have the characteristics of slow initiation speed, low initiation pressure, but large fracture width. During field operation, “high amplitude-high frequency” or “high amplitude-low frequency” can be used for rapid cracking in the early stage of

fracturing, and “low amplitude-high frequency” or “low amplitude-low frequency” can be adopted in the later stage of fracturing to repeatedly impact coal body to improve the fracturing effect. Moreover, several additional factors, including technical conditions, equipment characteristics, and material consumption, should also be taken into consideration when setting the HPPHF parameters.

Table 2. Fracturing effects of different HPPHF parameter combinations.

Scheme	Initiation Pressure/MPa	Initiation Time/s	Maximum Crack Width/mm	Crack Propagation Length/m
A	12.0	2.38	6.69	4.51
B	10.8	2.57	6.75	4.62
C	11.5	2.29	6.65	4.62
D	10.7	2.48	6.82	4.60

5. Industrial Tests

5.1. Fracturing Scheme in the Working Face

This study conducted industrial fracturing tests in No. 5210 working face of Shichangwan Coal Mine. Specifically, the mining height and the inclination angle of the coal seam in the working face were 1.8 m and 1–3°, and the hardness coefficient of the coal seam was equal to 2.6. The working face, with a width of 200 m and an advancing distance of 934 m, was mined using the fully-mechanized mining technology.

The fracturing boreholes were arranged in a row during the fracturing process. The borehole was 1 m from the top of the coal seam, and 0.8 m from the bottom of the working face, and the fracturing borehole direction was perpendicular to the coal wall. Given the cyclical footage of 6 m, the depth of the fracturing borehole was also set at 6 m, while the spacing between water injection holes was set at 5 m. To prevent caving on both sides of the coal wall in the working face, 10 m-space was reserved on the two sides of the working face, in which no water was injected. According to the numerical simulation results presented in Section 4, by taking into account both the fracturing effect and economic input, the water injection pressure of the high-pressure pulsed pump was set at 10 MPa, pulse frequency and pulse amplitude were set at 10 Hz and 3 MPa, respectively.

Figure 10 illustrates the structure of the HPPHF system. The overall system consisted of the fracturing system and sealing system. During the hydraulic fracturing process, water was first injected at a low pressure of 5 MPa, then the water injection pressure was increased to approximately 10 MPa in a fluctuant way. This water injection procedure is considered to be appropriate for coal fracturing-induced loosening process, which can ensure not only a certain loosening of coal at a certain depth but also can avoid dangerous coal wall caving and imposes no adverse effects on the roof management and mining safety.

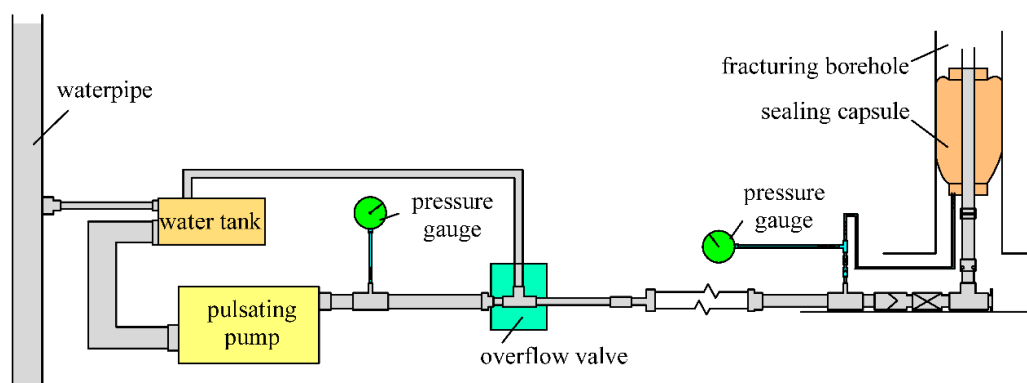


Figure 10. Structure of the HPPHF system.

5.2. HPPHF Implementation Results

Table 3 compares LCPs before and after fracturing. After fracturing, the amount of pulverized coal with a diameter not exceeding 13 mm was reduced by 11.3%, while the amounts of lump coal with diameter ranges of 13–30 mm, 30–80 mm, and 80–100 mm were enhanced by 4.7, 3.1 and 4.1%, respectively, and the amount of lump coal with a diameter exceeding 100 mm was only slightly reduced (namely, by 0.6%). Therefore, after HPPHF implementation, the percentage of lump coal with a diameter range of 13–100 mm was significantly increased. Due to the increase in LCP, the annual production of Shichangwan Coal Mine has been reduced, and the service life of the mine is expected to be extended for 3 years. The research results are of great significance for the sustainable development of similar aging mines.

Table 3. Comparison of LCPs before and after fracturing.

Diameter/mm	Lump Coal Percentages Before Fracturing/%	Lump Coal Percentages After Fracturing/%
<13	87.6	76.3
13–30	5.5	10.2
30–80	3.6	6.7
80–100	1.1	5.2
>100	2.2	1.6

6. Conclusions

In the present study, the high-pressure pulsed hydraulic fracturing (HPPHF) is proposed to enhance the lump coal percentage (LCP) of the hard coal seam in the fully mechanized mining face. The theoretical analysis, numerical simulation and engineering verification methods are mainly used to draw the following conclusions:

- (1) Coal structure is the main factor controlling LCP in coal mining. In contrast to the original coal, coal masses with more developed fractures are more easily damaged under the same external force. HPPHF can reduce the coal hardness, produce fatigue damages in the coal, enhance the development degree of coal fractures, and thereby, enhance the LCP.
- (2) As compared to the static case, a pulsed one can effectively reduce the limiting (maximum) pressure required for the coal fracturing. By imposing the repeated pulsed loading on the coal rock, large-scale damages can be generated at low energy consumption. Pulse amplitude, pulse frequency, and water injection pressure influence the high-pressure pulsed fracturing performance. Among the above three parameters, water injection pressure imposes the most significant effect on fracturing performance, followed by pulse amplitude and frequency.
- (3) Finally, industrial tests were performed on the No. 5210 working face to validate HPPHF performance. After implementing HPPHF, LCP and especially the amount of lump coal with a diameter range of 13–100 mm in the fully-mechanized mining face can be significantly enhanced; however, coal wave caving can also be inhibited, accompanied with a reduction of the production of lump coal in caving. Meanwhile, the amount of pulverized coal with small diameter particles also drops after the fracturing.

In the numerical model established in this paper, the coal body is regarded as a homogeneous medium, and the actual coal body is composed of a complex fracture system. Future research work will be conducted to establish a numerical model considering the complex fracture system of the coal body, and further study the effects of HPPHF parameters on coal fracturing.

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