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Research on Hydraulic Technology for Seam Permeability Enhancement in Underground Coal Mines in China

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Abstract: Coalbed methane (gas) is a high quality and clean resource, but it also causes disasters in coal mines in China. The low permeability of coal seams is the main reason that developing coalbed methane (CBM) as an energy resource is difficult, so increasing coal seam permeability is the key to CBM development in China. In this paper, the principal techniques for seam permeability enhancement are presented. The paper focuses on hydraulic technology for seam permeability enhancement (HTSPE), which is considered an economic and highly efficient technology for seam permeability enhancement. The process of HTSPE development is reviewed and the current status of the theories behind HTSPE and the technology and equipment for its use are summarized. The goal is to identify the gaps in HTSPE research and the problems in its implementation. In the future, integration and diversification of the technologies along with on-board intelligence and miniaturization may be the trends for the equipment. Finally, it is shown that tree-shaped borehole fracturing can be used to develop CBM in underground coal mines. This study could be used as a valuable example for other coal deposits being mined under similar geological conditions.

Keywords: coalbed methane; permeability enhancement; gas disaster; hydraulic fracturing; water jet slotting

1. Introduction

The development of coalbed methane (CBM) in China is doubly significant. On the one hand, as a high quality and clean energy resource, coalbed methane is of great importance for China's energy future [1,2]. The CBM resource in China are large; it ranks third in the world in proven geological reserves with 37 trillion m^3 [2]. Developing CBM has been included in the 13th Five Year Plan for National Energy Development [3]. On the other hand, as the cause for one of the five major kinds of accidents in underground coal mines (accidents including gas, flood, fire, dust, and ground collapse), problems related to gas seriously affect mine safety and coal production. As shown in Figure 1, gas accidents accounted for 10.4% of the total number of accidents in coal mines in China during 2006–2015, while gas accidents accounted for 27.9% of the total number of deaths [4]. For these reasons, improving the efficiency of CBM development is very important for optimizing the mix of energy resource used in China, for improving coal mine safety, and additionally for protecting China's atmosphere [5–9].

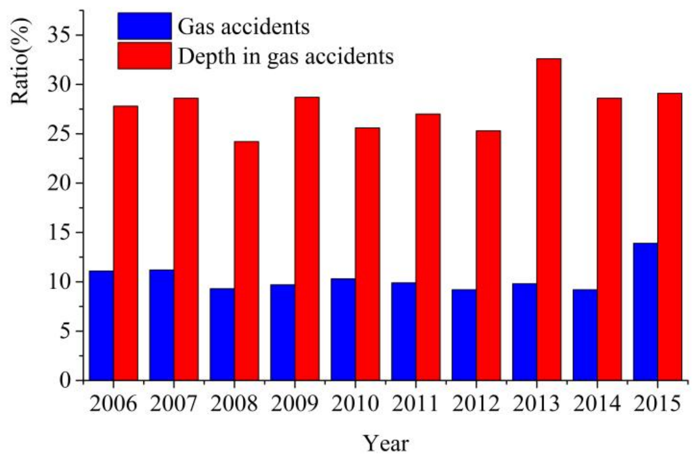

Figure 1. Accident and death rates in Chinese underground coal mines during 2006–2015.

Coalbed methane development in China can be divided into two classes: surface CBM development and underground gas extraction. The 13th Five Year Plan set target production to be 10 billion m^3 for surface and 14 billion m^3 for underground production by 2020. In 2015, total CBM production reached 18 billion m^3, of which 13.6 billion m^3 was extracted underground, as shown in Figure 2. Underground gas extraction has an important role to play in the development of CBM resource in China [10–12]. It is well known that CBM extraction is strongly influenced by coal seam permeability, but seam permeability is low in most mining areas in China (10^{-4}–10^{-3} mD). This is three or four orders of magnitude lower than in the United States, Australia, and other developed countries. Therefore, increasing seam permeability is probably the most promising technology to promote CBM development in China [8,13–15].

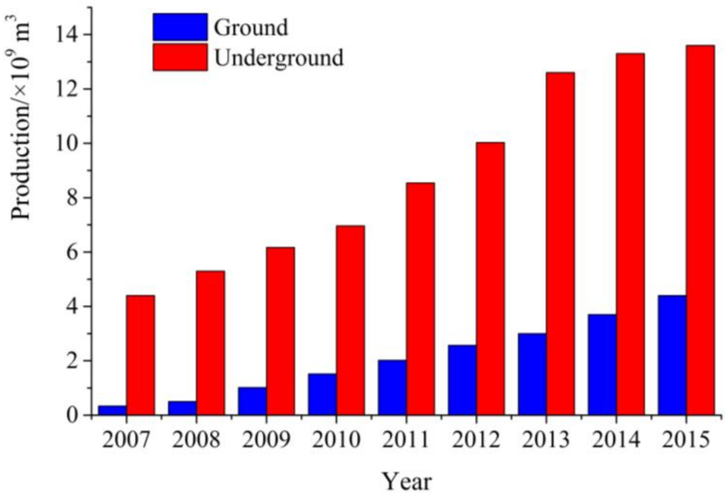

Figure 2. Production of coalbed methane (CBM) development in China in 2007–2015.

In China, the two main techniques for increasing seam permeability in underground coal mines are within coal bed and out-of-bed pressure relief. Pressure relief out-of-bed, also called protection layer mining, means mining the coal seam with low or no outburst risk first [16–18]. The method is simple, economical, and diminishes much of the gas pressure. It has been widely applied in China. However, for solitary coal seams or coal seams that have no low gas outburst risk layers (seams that have been mined first), only the pressure relief within coal bed techniques can be used. These methods include hydraulic technology for seam permeability enhancement (HTSPE), deep hole blasting (pre-splitting or cracking) [19], intensive drilling [20], and others [21]. The effect of increasing seam permeability by deep hole blasting is obvious, but this technique may make later coal mining unsafe because of the possibility of residual detonations. The intensive drilling technique may also not be appropriate because it may not appreciably increase seam permeability and because it requires a huge number of drill holes and can be very expensive.

HTSPE is a method for increasing seam permeability in which high-pressure water is used to break coal or rock and thus connect natural pores and fractures. This technique typically includes hydraulic flushing [22], water jet slotting [23–25], and hydraulic fracturing [26]. After decades of development, HTSPE has been greatly improved and the use of HTSPE has increased in recent years because it is simple and increases seam permeability effectively. However, there are still some technical bottlenecks to the use of HTSPE in some mining areas because of the complex and diverse geological conditions in China. This paper reviews the history of HTSPE and summarize the current status of the theories, technologies, and equipment for HTSPE. Then, an analysis of the main theories and engineering problems are presented and some avenues for future developments of HTSPE are proposed.

2. Process of HTSPE Development

2.1. Early Experimental Stages

The experimental study of underground hydraulic fracturing started in the former Soviet Union in the 1960s when hydraulic fracturing was used to increase seam permeability in 15 underground coal mines in the Carla Ganda and Buzz mining areas. From the end of the 1950s to the end of the 1980s, HTSPE was used locally in China as a preventative measure against gas outbursts in coal road tunnels, rock crosscuts to uncover coal, and other areas. A simple "light type" hydraulic drill was designed in 1958. A water jet was used to scour coal before mining began and a rock crosscut with outburst risk was completed safely in 1965. In 1969, water jet slotting experiments were carried out to expand the range over which boreholes could reduce gas pressure in the Hebi No. 6 coal mine by the Fushun Coal Research Institute. In 1977, water jet slotting experiments were used to prevent coal and gas outburst in the Hongwei coal mines. During 1971–1985, water jet slotting and hydraulic fracturing were used to improve the efficiency of gas extraction in the Hebi No. 4, Hongwei No. 2, Yangquan No. 1, Fushun North, and Longfeng coal mines as well as the coal mines near Jiaozuo Zhongma village.

2.2. Popularization and Application Stages

Between the 1990s and the early 2000s, and based on the results of the initial tests just described, HTSPE gradually became more popular. However, it was only used in small trial applications at a few coal mines with significant gas control problems near Fushun in Liaoning province and Jincheng in Shanxi province (plus a few other mines). It failed to gain wide acceptance. The authors think that this lack of acceptance was mainly caused by the following factors. First, the coal industry was in a slump and demand for coal had deteriorated in China at that time. Second, the pressure that could be delivered by many of the pumps used in underground coal mines was low and the flow was small, insufficient to meet the demands of HTSPE. The capacities of some of the other equipment also could not meet HTSPE requirements. In addition, theories on how seam permeability could be increased were not fully developed and therefore could not provide the necessary theoretical support. In the end, safety and other facilities were not perfect.

2.3. Rapid Development Stage

After 2003, several things changed. The domestic coal industry developed rapidly and national policy programs such as "the basic index of coal gas drainage", "the prevention of coal and gas outburst" and other related programs were implemented. HTSPE development increased greatly. Extensive research on HTSPE theory and technology was conducted by several scientific research organizations. At present, HTSPE has been applied or tested in more than 30 mining areas, and it has achieved good results in most of them. From a geographic perspective, HTSPE is used more in Central China, East China, Southwest China, and North China than elsewhere. There are some mining areas where it has worked well like Songzao, near Chongqing, southwestern China.

More than 10 different techniques for HTSPE have been developed. These techniques can be divided into two broad classes, namely water jet methods and hydraulic fracturing. Water jet methods include hydraulic flushing, hydraulic cutting, water jet slotting, water jet reaming, hydraulic loosening, etc., while hydraulic fracturing methods include hydraulic extrusion, hydraulic fracturing, etc. [27,28].

Table 1 shows the major milestones of HTSPE in China. Among the techniques mentioned, water jet slotting and hydraulic fracturing are the methods used most often. Those two techniques will be discussed in more detail in the following sections.

Table 1. The major milestones of hydraulic technology for seam permeability enhancement (HTSPE) in China.

Technology	Time	Technique	Principle	Status of application
Water jet	1959	Hydraulic flushing	High-pressure water jet is used to cut a large slot in the coal at the face of the heading, then gas migration increases greatly with the pressure around the slot being relieved.	Some experiments have been conducted for coal roadway tunneling.
	1965	Water jet scouring	Water jet was used to break coal on the surface before coal mining or coal roadway tunneling.	Water jet scouring has been used for rock cross-cut coal uncovering successfully.
	1978	Water jet slotting	The technique is using a jet of high-pressure water to break coal in coal seam and increase the free face area to allow for increased gas emissions.	Some experiments have been conducted to prevent coal and gas outburst.
	After 2003	Water jet slotting		Water jet slotting has been widely used for coal seam permeability enhancement.
Hydraulic fracturing	1970–1985	Hydraulic fracturing	The principle of hydraulic fracturing is to use high pressure water to form a fracture network in the coal seam to increase the permeability of coal seam.	Hydraulic fracturing has been used for CBM development initially.
	1997	Hydraulic extrusion	Hydraulic extrusion is also known as medium-pressure water injection. Medium-pressure water is injected into coal seam to make the seam loose.	Some experiments have been conducted to prevent coal and gas outburst during coal roadway tunneling.
	After 2009	Hydraulic fracturing	The principle of hydraulic fracturing is to use high pressure water to form a fracture network in the coal seam to increase the permeability of coal seam.	Hydraulic fracturing has been widely used for coal seam permeability enhancement.

3. Seam Permeability Enhancement by Water Jet

3.1. Technology and Its Application

The technique most commonly used to enhance seam permeability is using a jet of high-pressure water to break the coal seam and increase the free face area to allow for increased gas emissions. This can lead to quick pressure relief and an increase in permeability. The techniques for water jetting can be divided into water jet slotting and hydraulic flushing. The "slot" in water jet slotting is cut around the radius or parallel to the axis of a borehole by a water jet in the borehole. The slot for hydraulic flushing is created by a water jet applied directly on the face.

In recent years, a breakthrough in water jet slotting has been made and it has become one of the main techniques used to increase coal seam permeability. At present, there are two modes for water jet slotting: slotting along the axis of the borehole is shown in Figure 3 and slotting around the radius of the borehole is shown in Figure 4.

The increase in coal seam permeability produced by high-pressure water jet slotting along the borehole axis has been simulated and studied in the laboratory. Results show that the amount of gas emitted increase by 25% and the primary gas emission rate increased by 100–150% [29]. Further, because of its proven ability to grind, penetrate, and erode effectively, abrasive water jet slotting parallel to the borehole axis has been applied in the Pingdingshan mining area in Henan province.

As shown in Figure 5, results indicate that the amount of gas extracted from a single borehole can be increased by a factor of four or five by slotting [30].

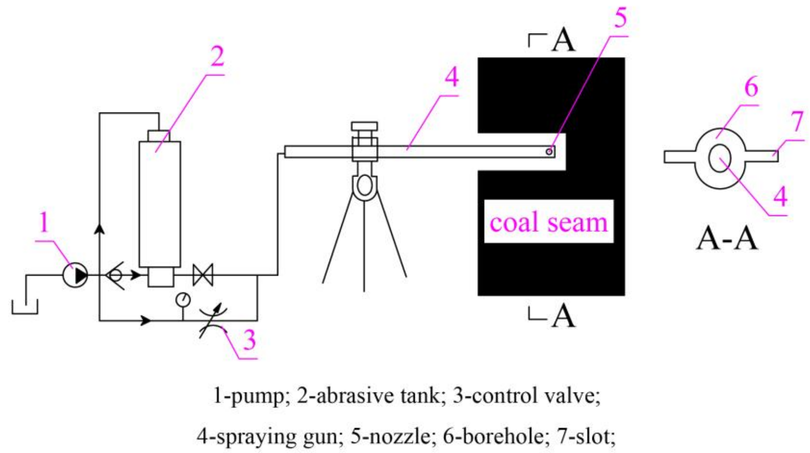

Figure 3. Sketch showing the system used for abrasive water jet slotting.

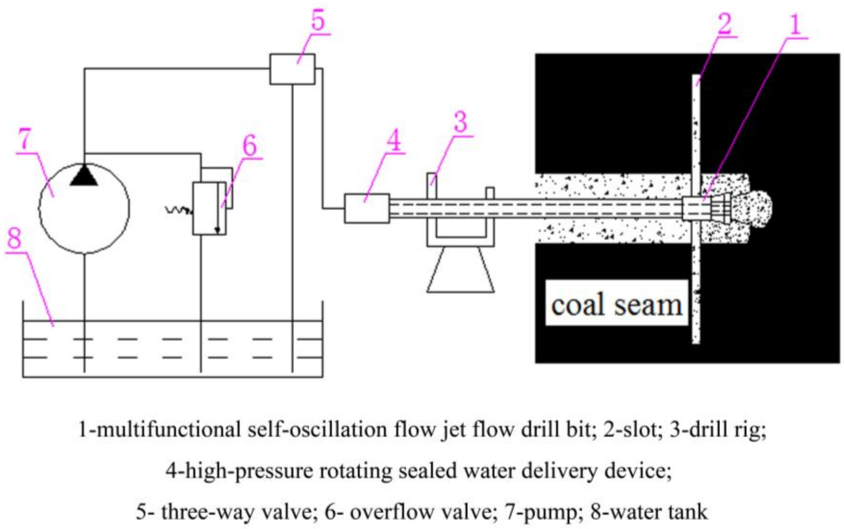

Figure 4. System for self-excited oscillation pulsed jet slotting.

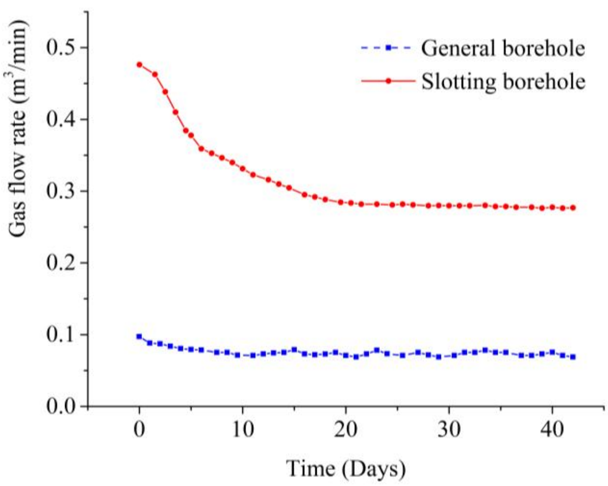

Figure 5. The gas flow rate between borehole with abrasive water jet slotting and general borehole [30].

Li and Lu conclude that self-excited oscillating pulsed water jets will concentrate energy and, along with the strong oscillations, will generate an erosive and cavitation effect that will increase the ability to break coal by more than 72%. It is more effective to break and slot a coal seam by multiphase oscillation jets. The coal seam permeability and the free surface for gas emissions will increase and a large volume of the coal seam will undergo rapid pressure relief after slotting [31]. In addition, the absorbed gas will be desorbed more readily by the cavitation in the multiphase oscillation jet [32].

On this basis, two special techniques have been developed for different conditions in coal seams.

(1) In some instances, difficult drilling conditions and low hole drilling rates (with the depth of borehole being only 45–60 m) lead to gas extraction in soft coal seams being difficult. Figure 6 shows a novel technique of drilling in the roof or floor with a high pulse pressure water jet to improve gas extraction which has been developed and applied in the Songzao, Huainan, Yangquan, and Pingdingshan mining areas, as well as in other mining areas. As shown in Figure 7, the results indicate that borehole depths reach 120–147 m, the diameter of the slot is up to 3–4 m, and the amount of gas extraction increases more than 520% [25].

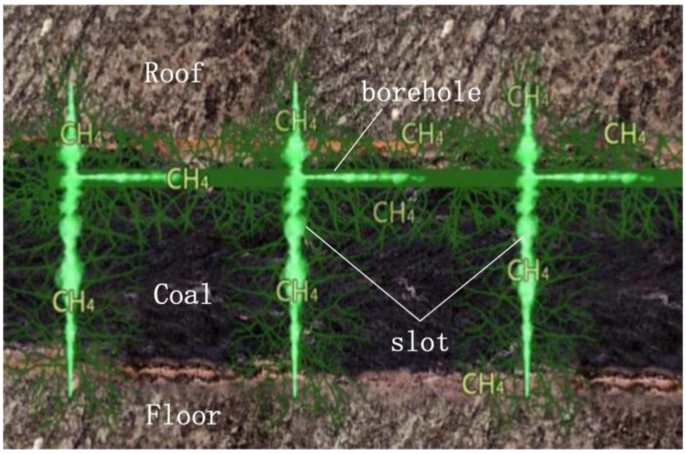

Figure 6. Novel technology for drilling in the roof or floor with high pulse pressure water jet slotting to improve gas extraction in soft coal seams.

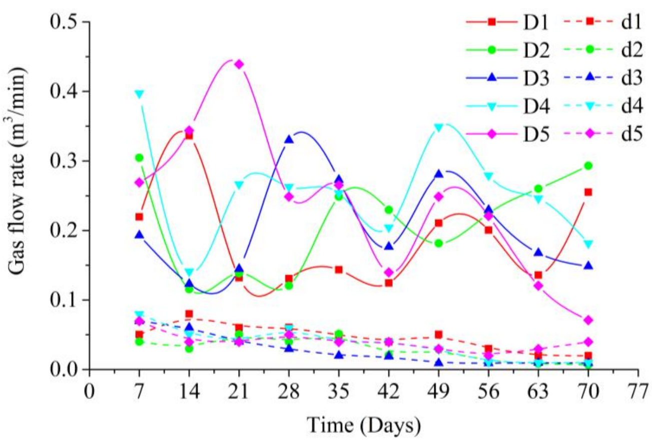

Figure 7. The gas flow rate between boreholes drilling in the roof or floor with pulse pressure water jet slotting into coal seam and general in-seam boreholes. Lines D1–D5 represent the gas flow rate of the boreholes drilling in the roof or floor with pulse pressure water jet slotting into coal seam, and Lines d1–d5 represent the gas flow rate of the general in-seam boreholes [25].

(2) When rock crosscuts are driven to uncover coal, the free surface around cross-measure boreholes is too small to lead to big density pre-drainage boreholes, which as a result leads to low gas extraction efficiency. The novel technology of cross-measure drilling with high-pressure pulsed water jets has been developed to improve gas extraction in low permeability coal seams (Figure 8). This technique has been used in the same four mining areas mentioned above (Songzao, Huainan, Yangquan, and Pingdingshan) as well as other mining areas. The results show that gas extraction increases by 293% with the number of pre-drainage boreholes needed decreased by 50% (Figure 9) [24]. In addition, the time needed to drive the rock crosscuts decreases from more than six months to about one month [24].

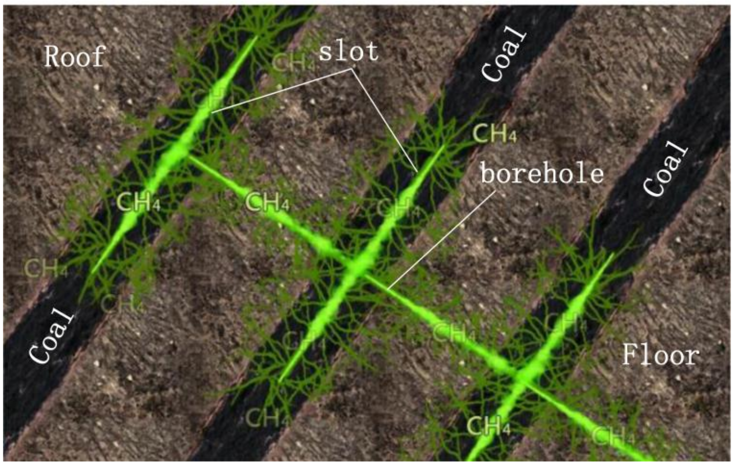

Figure 8. Novel technology for cross-measures drilling with a high pulse pressure water jet to improve gas extraction in low permeability coal seams.

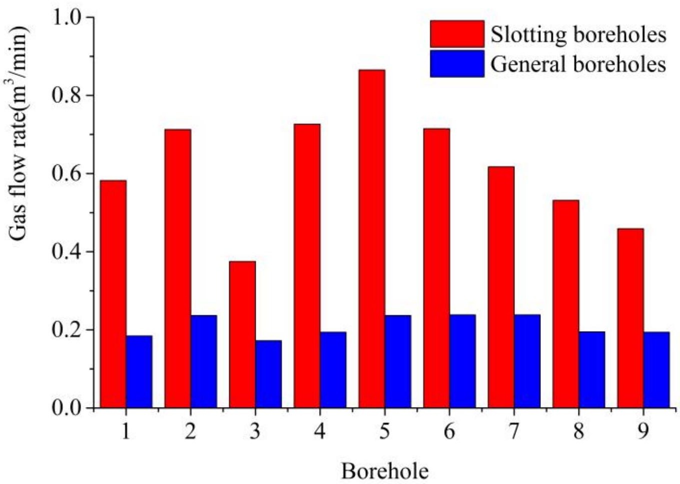

Figure 9. The gas flow rate between cross-measure boreholes with high pulse pressure water jet slotting into coal seam and general cross-measure boreholes [24].

3.2. Theories of Hydraulic Slotting for Seam Permeability Enhancement

Increasing seam permeability by water jet is a typical example of the successful application of water jets in the field of mining engineering. The theoretical study of seam permeability enhancement by water jet is mainly focused on the mechanism of coal breaking by water jet and how gas migration occurs in a coal seam after water jet slotting.

3.2.1. Theories of Coal Breaking by Water Jet

The study of coal breaking by water jet is the basis for seam permeability enhancement by water jet. At present, several theories about how water jets break rock are widely accepted by the academic community. In China, the theory of stress wave breaking has been widely used [33,34]. The mechanisms for breaking coal by water jet were studied based on an analysis of the stress field in the coal under the dynamic load of a jet of high-pressure water. Using this analysis, which postulated a spherical wave, a mechanical model for coal hit by a water jet was developed. The results show that the coal is broken mainly by the dynamic load. Furthermore, shearing and tensile stress of the wave play a leading role [35].

It is assumed that the elastic modulus and compressive strength of anisotropic rock obey Weibull Distribution, and so the failure criterion and threshold pressure of an anisotropic rock (p) being broken by water jet can be calculated from (Equation (1)) which is based on the percolation theory developed by Chang [36].

$$p_m = R_{c0}\left[-\ln\left(1 - M_f\right)\right]^{\frac{1}{m}} \tag{1}$$

where m is the anisotropic coefficient of the rock, R_{c0} is the average compressive strength of the rock, and M_f is the ratio of the percolation theory.

Based on a theory of spherical cavity-expansion, Mu et al. [37] think that the dynamic mechanical response of coal being hit by a high-pressure water jet can be divided into a crushing region, a crack region, and an elastic region, and the mechanical reactions of the regions have been analyzed according to this theory. This allows one to calculate the minimum impact pressure required for a high-pressure water jet to break coal.

However, Lu et al. [38] think that brittle failure caused by tensile stress may be the main mode for breaking coal with a high-pressure water jet. They believe that the cracks generated propagate as radial cracks, cone cracks, or transverse cracks. The maximum shear stress is generated at a specific depth below the impact zone and the tensile stress is generated around the impact zone. The coal will break when the tensile stress is greater than the tensile strength of the coal. As a kind of lastics with a large amount of porosity and many cracks, coal contains pre-existing flaws. If this is the case, it is more appropriate to model coal breakage based on continuum damage mechanics. For example, the mechanical parameters were obtained from porosity tests and uniaxial compression tests on a coal from a coal mine in Chongqing, China. An equation for calculating the threshold value for coal damage (σ) was established by Liu [39]:

$$\sigma = \frac{(\tau - c)(1 - hD_0)}{\tan\varphi\left\{1 - h\left[D_0 + C_1\varepsilon_p^{\beta} + C_2\left(\varepsilon - \varepsilon_p\right)\right]\right\}} \tag{2}$$

where $\beta = \dfrac{\sigma_p}{E\varepsilon_p - \sigma_p}$; $C_1 = \dfrac{1 - D_0}{1 + \beta}\varepsilon_p$; $C_2 = \dfrac{1 - D\left(\varepsilon_p\right)}{\varepsilon_u\varepsilon_p}$; σ_p is peak stress; σ is compressive stress of coal; ε is tensile strain; ε_p is the strain values of the peak stress; ε_u is ultimate strain; D_0 is initial damage; $D\left(\varepsilon_p\right)$ is the damage of the peak stress; E is elastic modulus; h is the coefficient of the crack closing factor which can be treated as a material constant; τ is shear strength; c is cohesion; and φ is internal friction angle.

3.2.2. Gas Migration in a Coal Seam after Water Jetting

To study gas migration in a coal seam after water jetting, the effective stress around a slot cut in the coal by the jet has been analyzed by numerical simulation to determine the extent of pressure relief. The numerical techniques used include fast Lagrangian analysis of continua (FLAC), rock failure process analysis (Dalian Mechanics Software Co. Ltd., Dalian, China), routines included in software from Ansys Inc. (Canonsburg, PA, USA), and similar techniques. Then, the factors controlling gas migration can be found based on the relationships between effective stress and gas seepage.

Based on analyzing the "bottleneck effect" caused by the stress concentration around a borehole, FLAC has been used to study the effect of the stress in the direction perpendicular to the slotting plate and the angle between major principal stress and the slots on the pressure relief. The results indicate that the rate of pressure relief increases with the stress in the direction perpendicular to the slotting plate. The angle between the slotting plate and the direction of the principal stress also has effects on the pressure relief rate. The effect of pressure relief is lowest when the angle is 60° and the effect is highest when the angle is 0°. Moreover, when the angle is 0°, it has been pointed out that the region of pressure relief decreases as the rate of pressure relief increases [40–42].

Lu and Jia think that the gas migration in a coal seam after water jet slotting should be in three-phase couple conditions (gas-solid-liquid) [43]. The stripe's drainage time for different coal seam conditions as well as different borehole layouts was studied. The coal slotting size was calculated theoretically by combining it with the model experimental results for high-pressure water jet slotting. Based on the momentum theorem and continuum damage mechanics theory, this allowed the slot size for different coal seam conditions to be set. Then a dynamic evolution model of permeability and porosity as well as D-P criteria were introduced to build the fluid-solid coupling model for gas seepage in the lower permeability slotted coal seams. The coupling model was calculated based on the secondary development from the COMSOL Multiphysics software (version 4.2 a, Stockholm, Sweden). Results show that borehole radius increases with the drainage time and there is a significant exponential correlation between the two. Gas migration in the coal seam was affected by the arrangement of the slotted boreholes, and the cross arrangement was most effective. An equation relating drainage time to slot size, borehole spacing, permeability, coal depth of burial, and gas pressure gradient was formulated to guide borehole layout.

Furthermore, slot size was calculated by the dimensioning formula in W2704S return airway strip of Datong one coal mine (Chongqing, China), and the borehole arrangement was optimized based on the numerical results. Field experiment results show that the relative error between the numerical calculation time and the actual time is 7.9%, which verifies that the layout of the slotted boreholes was appropriate [44].

4. Seam Permeability Enhancement by Hydraulic Fracturing in Underground Coal Mines

During the 1970s and 1980s, hydraulic fracturing was used to increase seam permeability in underground coal mines in China. Compared with water jet slotting, hydraulic fracturing has several advantages. Some of these advantages are the volume of rock that can be fractured is larger, permeability can be substantially increased, and the use of hydraulic fracturing can reduce the number of boreholes required to reduce gas pressures. However, hydraulic fracturing also has some drawbacks.

(1) In underground mines, hydraulic pumping pressure for fracturing is elevated empirically to fracture the largest volume of rock possible. However, as a side effect, this high pressure incurs the risk of damaging the integrity of the roof and floor of the coal seam, making the stability of roadways difficult to maintain.
(2) The propagation of hydraulic fractures is influenced by the in situ stress field and is therefore mainly in the direction of the principal stress. This means there will be stress shadow zones in which the permeability will not be appreciably increased. These zones will lead to gas extraction difficulties and possibly to gas accidents.
(3) The fundamental conditions of walls of the borehole used for fracturing cannot be improved, and this leads to the fractures created by the hydraulic fracturing being difficult to initiate and propagate.

Chinese scholars interested in research on increasing seam permeability by hydraulic fracturing in underground coal mines should focus on the aspects described above.

4.1. Technology and Its Application

4.1.1. Sealing Technique of Hydraulic Fracturing in Underground Coal Mines

The success of hydraulic fracturing and the effectiveness of gas extraction depend on sealing the borehole immediately.

To improve the sealing after pulsating hydraulic fracturing, an expansive cement composite material (called PD composite material) was selected as a sealing agent. The results show that the pressure-bearing capacity of PD material is proportional to the length to be sealed and inversely proportional to the hole diameter. The difficulty of crack propagation in the sealed section increases with the sealing length and when the hole diameter is smaller. The results also show that higher ripple frequencies require higher performance from the sealing material. Higher ripple frequencies are more conducive to continued fracturing and expansion of cracks in the sealed section of the borehole [45].

Ge [46] considered the problems associated with common sealing materials used in boreholes. These include shrinkage, poor sealing, inability to seal the length of hole required, and high cost. A new hydraulic fracturing sealing material consisting of cement, an early strength water-reduced agent, polypropylene fiber, and mixing water has been under development. Through laboratory experiment, the sealing material ratio at the best obtainable compressive strength and shrinkage percentage were optimized. A mechanical model for hydraulic fracturing borehole sealing has also been constructed that is used to determine the relationship between the maximum water pressure that can be supported by the sealing material and sealing parameters. A proper sealing length is determined by site experiments. The results demonstrate that the optimal ratio for the new material by weight is 1.0:0.6:0.03:0.005 for concrete, water, early strength water-reduced agent, and polypropylene fiber. The maximum water pressure that can be supported by the sealing material increases with increasing strength, modulus of elasticity of the sealing material, and sealing length until a nearly constant value is attained when the sealing length reaches a certain point. Taking the Chongqing Songzao mining area in China as an example, reasonable sealing lengths for the fracture borehole for through bed fracturing and along beds fracturing have proven to be 10 and 13 m, respectively. This is consistent with the theoretical analysis.

4.1.2. Fracturing Technique in Underground Coal Mines

Based on the fatigue damage suffered by coal impacted by cyclic loading, a pulse hydraulic fracturing technique was developed to increase seam permeability. The pulse hydraulic fracturing technique is used to improve the coal permeability and thus to enhance gas drainage (as shown in Figure 10). Compared to the traditional hydraulic fracturing, it has two advantages. First, it takes the advantage of fatigue effect. Fatigue characteristic is a dynamic material property. Studies show that fatigue damage occurs when the coal and rock mass are under alternating loads, and the strength is reduced. Therefore, the fracture initiation pressure of pulse hydraulic fracturing technique will be lower than that of traditional hydraulic fracturing. Second, the pulse pressure produced by the pulse pump spreads in waves in the fractures. The pressure may be enlarged because some of the reflected waves are likely to superimpose to strengthen some points. In this case, a lower pump pressure may produce a higher pressure, exacerbating the coal failure. The technique has been tested in the Tiefa mining area, Liaoning province. As shown in Figure 11, the results indicated that the amount of gas extracted increased by 175% [47].

A novel method for decreasing coal seam initial cracking pressure was developed in which perforations, drilled by high-pressure water jets, are used as a means to avoid destroying coal seam roofs and floors (as shown in Figure 12) [48]. To test whether hydraulic fractures could be propagated along the direction of major principal stress, a hybrid technology between water jet slotting and hydraulic fracturing based on self-excited oscillation pulsed jet slotting was developed. The oriented boreholes are drilled around a hydraulic fracturing borehole, and a high-pressure water jet is used to perforate parallel slots to the direction of coal bed before hydraulic fracturing is performed (Figure 11).

Because of shear failure at the perforation tip, cracks initiate at the perforation tip during hydraulic fracturing. Moreover, the perforation causes the maximum principal stress at an angle approximately parallel to the perforation axial, which leads to the orderly propagation of the crack in the coal. This technique was first applied in the Songzao mining area [26]. As shown in Figure 13, the results indicated that the quantity of gas extracted increased by over a factor of 11 and the concentration of that gas increased by 212% [26].

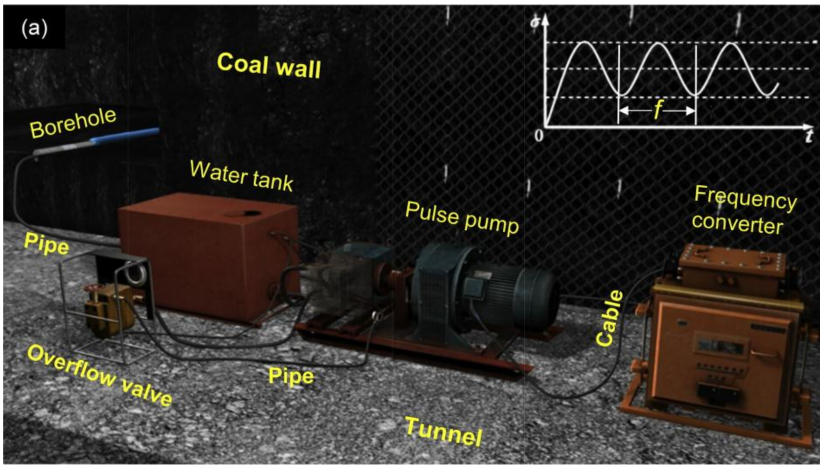

Figure 10. The work state of pulse hydraulic fracturing technology in a coal mine (simplified).

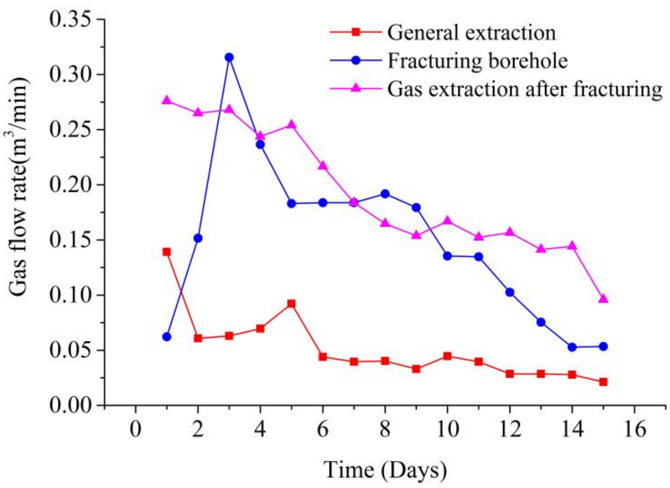

Figure 11. Changes in gas flow rate over time between fracturing borehole and general boreholes [47].

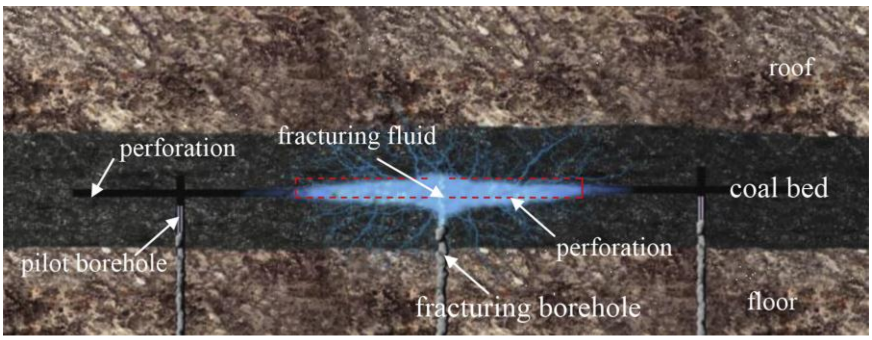

Figure 12. Method for orienting a hydraulic fracture within a coal bed [48].

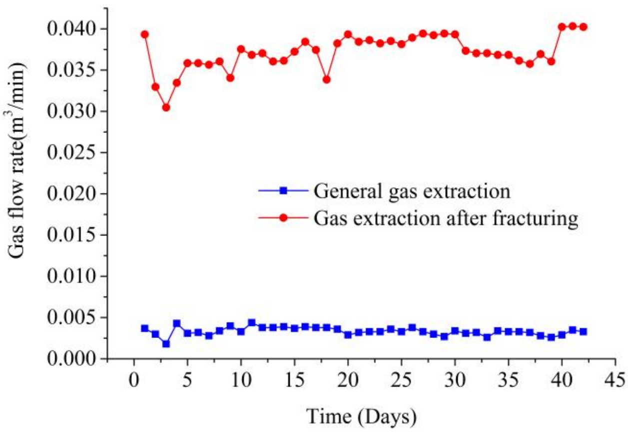

Figure 13. Changes in gas flow rate over time between fracturing borehole and general boreholes [26].

4.2. Theories of Hydraulic Fracturing in Underground Coal Mines

4.2.1. Initiation of Hydraulic Fracturing in Underground Coal Mines

According to the first strength theory, through analyzing the stress around the borehole, the breaking mechanism of the coal under high-pressure can be studied and the critical values can be obtained. The results show that initial cracking pressure is not only influenced by in situ stress but also influenced by the rock around the borehole. Initial cracking pressure is influenced by the weakest coal delaminations around the radius of the borehole and weak interfaces between delaminations along the axis of the borehole. The Initial cracking location is influenced by the weak interfaces between delaminations along the axis of the boreholes and minimum tensile strength and vertical side stress coefficients along the radial directions [49].

Lu et al. [50] presented that initial cracking pressure and crack locations are significantly influenced by in situ stress, the arrangement of fracturing boreholes, and the distribution of the coal seams in underground coal mines (Figure 14). The stress state around fracturing boreholes has been analyzed using in situ stress coordinate transformations. A mathematical model was then developed to evaluate initial cracking parameters around the borehole assuming the maximum tensile stress criterion. Subsequently, the influences of in situ stresses and the presence of coal seams on initial cracking pressure and crack locations were analyzed using the proposed model. Finally, the proposed model was verified with field test data. The results suggest that the pressure required to initiate cracking increases with depth and with coal seam dip angle. However, the initial pressure decreases with an increase in the azimuth of the major principle stress. The results also indicate that the initial cracking locations are concentrated in the second and fourth quadrants (using polar coordinates), and these locations shift direction towards the strike of the coal seam as the coal seam dip angle and the azimuth of the maximum principle stress increase.

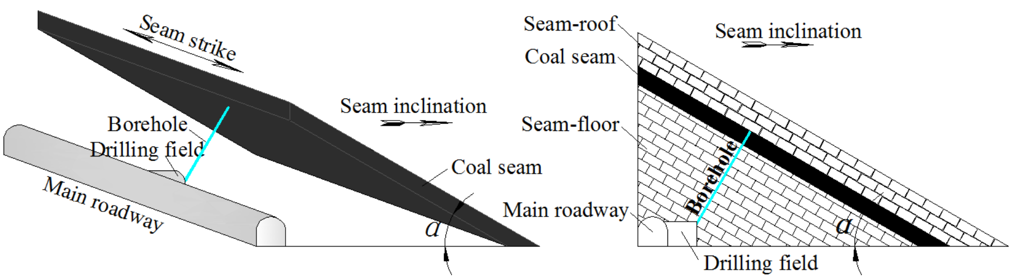

Figure 14. Relationship between the fracturing boreholes and coal seams.

After analyzing perforation stresses, two models were built, one for predicting initial cracking pressure for hydraulic fracturing with perforations and the other model for fracturing without perforations. A comparison of initial cracking pressures between the two models was made. The results showed that perforation did decrease the initial cracking pressure required owing to change in the stress distribution and that the main stress ratio affects the decrease of initial cracking pressure [48]. Those results can be expressed by the following equation.

$$p_w \geq \frac{1}{2(\cos 2\theta' + 1)} \begin{bmatrix} (\sigma_x + \sigma_y + \sigma_{z\theta}) - 2(\sigma_x + \sigma_y - \sigma_{z\theta}) \cos 2\theta' \\ -2(\sigma_x - \sigma_y)(\cos 2\theta + 2\cos 2\theta \cos 2\theta') \\ -4\tau_{xy}(1 + 2\cos 2\theta) \sin 2\theta - 4\tau_{z\theta} \sin 2\theta' - \frac{\tau_{z\theta}^2}{\sigma_{z\theta}} \end{bmatrix} \quad (3)$$

where p_w is the water pressure in the borehole; σ_x, σ_y, $\sigma_{z\theta}$, τ_{xy} and $\tau_{z\theta}$ are radial, tangential and axial components of normal and shear stress, respectively; θ and θ' are azimuth and dip angle of perforation, respectively.

4.2.2. Propagation of Hydraulic Fracturing in Underground Coal Mines

In Lin and Du's experiments, analogous materials consisting of powdered coal, cement, and gypsum with different material proportions were used. The quasi tree-axis hydraulic fracturing tests were carried out on the coal specimens and the raw coal specimens. The results indicated that reasonable material proportions are Coal:Cement:Gypsum = 1.5:1:1. The crack always propagates along the direction of the major principle stress and fracturing fluid flow is influenced by the character of the crack surface in the coal seam [51].

Yang et al. [52] reported that the high and oscillating hydraulic pressures, instability propagation, and the complex conformation of hydraulic fractures were mainly influenced by the natural cleats and fractures in the coal seam. When horizontal crustal stress differences are small, hydraulic fractures can initially crack in multiple directions and propagate randomly along cleats or natural fractures. When the horizontal stress differences are greater, the hydraulic fractures tend to occur along the vertical direction of minor horizontal stresses.

Lu et al. [53] reported that when the hydrofracture crack propagates to the interface between the coal bed and the roof or floor stratum, the crack may enter the roof or floor thus imposing a limit on the scope of increased permeability in the coal and causing support problems for subsequent coal mining. A two-dimensional model of a coal-rock bed that contains hydrofracture cracks was constructed. Then an investigation that combined fracture mechanics and the system of flow and solid in rock failure process analysis (by RFPA2D-Flow, Dalian, China) was carried out to study: (a) the failure mechanism at the interface between rocks and coals; and (b) the critical water pressure that is required to propagate hydrofracture cracks. The results indicated that the main factors that affect the direction of hydrofracture crack propagation are the angle of intersection between the coal-rock interface and the horizontal crustal stress differences, the tension-shear mixed crack fracture toughness along the coal-rock interface, and the differences in the modulus of elasticity between different portions of the coal-rock bed. The possibility of a crack directly entering the coal-rock interface increased with an increase in the angle of intersection or increasing horizontal crustal stress differences. The trend that a crack would propagate along the coal-rock interface became stronger with a decrease in the fracture toughness at the coal-rock interface and with an increase in the difference between the modulus of elasticity of the coal bed and that of the roof or floor strata.

5. Deficiencies and Prospects of HTSPE

5.1. The Deficiencies

5.1.1. Lack of Systematic Study on Seam Permeability Enhancement by Hydraulic Technology

(1) When high-pressure water interacts with undisturbed coal, the gas is coupled with solid particles and with liquid. How coal fails in this three-phase coupled state is not clear.

The gas in coal appears to be present in two states: free and adsorbed. This system remains in balance given constant temperature and gas pressure. However, Zhou et al. [54] reported that the strength of coal containing water and gas can change drastically. Coal strength decreases as the water content increases. The deformation and failure of coal containing gas are both influenced by free gas and adsorbed gas. The free gas can increase the pore pressure as a volume force, whereas the adsorbed gas may cause changes in the mechanical properties and mechanical response with gas adsorption and desorption [55,56]. Therefore, it is necessary to study the failure mechanisms of three-phase coupled coal.

(2) There is a lack of systematic research on seam permeability enhancement by water jet slotting. Water jet slotting should be a pressure relief method for increasing seam permeability. At present, research on seam permeability enhancement by water jet slotting mainly concentrates on the mechanism of coal breaking and the stress variations around the slot. However, how to make the slots relieve pressure from the coal seam and how to change the stress state around the slots is not clear [57]. Furthermore, how the crack field around the slots change with changes in the stress state is unknown. Finally, how gas flows in and around the crack field still needs to be studied.
(3) Hydraulic fracturing should also be a pressure boost method for seam permeability enhancement in underground coal mines. Most scholars think that a coal seam can be cracked and fractures can be propagated as they are in an ordinary rock. Then, the seam permeability can be increased. However, there are some essential differences:

    (a) Coal is a porous media and there are many pores and natural fractures in a coal seam, so the failure criteria are different from those in a rock during hydraulic fracturing.
    (b) Coal seams in underground mines are always between roof and floor rocks. Compared with the rocks, the coal seam is very thin. In addition, the coal's mechanical properties are very different from rocks.
    (c) The roadways around coal seams in coal mines may change the stress state of the coal seam.

Therefore, it is believed that the high pressure of hydraulic fracturing may account for the fractures in the coal seam. The fractures can increase the seams' permeability. Furthermore, the fractures leave space for coal seam pressure relief. Because of coal's significant plasticity and hygroscopic properties, coal seams may swell in the space and then the natural fractures can also connect to increase the seams' permeability.

5.1.2. Applicable Conditions of HTSPE is Limited

Each time HTSPE is used, it may have the desired effects on seam permeability but it also has limitations. For example, sufficient pressure relief and greater uniformity of permeability enhancement are advantages for water jet slotting and hydraulic flushing but the radius of influence for these techniques of 1.5–3 m is a disadvantage.

The radius of permeability enhancement that can be generated by hydraulic fracturing can be tens of meters. However, it is difficult if not impossible to achieve uniform permeability enhancement throughout the influenced zone. This is because the directions of crack propagation are not uniform; the cracks generally propagate parallel to the direction of the major principle stress because cracking is influenced by in situ stress field.

In addition, the different and complex geological and mining conditions in each individual mining area in China make it difficult to determine where the appropriate conditions for HTSPE use might exist.

Finally, HTSPE lacks a method to evaluate its effect on seam permeability. Therefore, it is difficult to design an effective layout of gas extraction boreholes that could improve the efficiency of gas extraction. Table 2 shows the merits and demerits of HTSPE in China.

Table 2. The merits and demerits of HTSPE in China.

Technology	Merits	Demerits
Water jet slotting	1. The operation is simple and can be controlled manually. 2. A net-like pattern of boreholes can be arranged for slotting and no blind zone will be generated. 3. Good applicability	The scope of seam permeability enhancement is small, and the number of boreholes is still very large.
Hydraulic fracturing	1. The scope of seam permeability enhancement is wide and the effect is good. 2. The number of gas extraction borehole decreased after Hydraulic fracturing.	1. Hydro-fractures tend to propagate along the direction of maximum principal stress, while few hydro-fracture can propagate along the direction of minimum principal stress. Thus, it leads to the area not being enhanced. 2. Hydraulic fracturing may destroy the coal seam roof and floor because of its high initiation pressure.

5.1.3. HTSPE Equipment Improvements

Part of the aim of any advanced technology is advancing the state of the art of the equipment and, presently, HTSPE equipment is too large and awkward to operate easily. Although the sophistication of HTSPE equipment has been improved greatly, some aspects could be better. The two most important areas are the addition of geophysical exploration devices and smaller pumps with higher power. In addition, it must be noted that every device used in underground coal mines in China needs to be flameproof. Regulations in China are very stringent. This means that the majority of high-tech equipment in the world is not suitable for use in underground coal mines in China. In addition, the roadways in many mines are too narrow to transport and install very large pieces of equipment. Finally, the workers in many cases do not have the sophistication or experience required to control a complex device.

5.2. Development Direction of HTSPE in the Future

5.2.1. Uniform Permeability Enhancement in the Future

Uniform permeability enhancement means that the seam permeability increases uniformly—the volume of the seam in which permeability is enhanced has no shadow zones. If uniform permeability enhancement could be attained, it would improve the efficiency of gas extraction and reduce or prevent gas accidents.

Based on the techniques of self-propelled water jet drilling and hydraulic fracturing, tree-shaped boreholes fracturing technology can be developed to achieve the goal of uniform enhanced permeability. First, a drill rig has to drill a pilot hole from a roadway into the coal seam. Then, a water jet self-propelled drill bit will be introduced into the pilot hole to drill many directional boreholes in the coal seam [58]. The resulting pattern of holes in the seam will resemble the branches of a tree. This will enable a grid of fractures to be generated by hydraulic fracturing. As shown in Figure 15, this method makes it possible to avoid unbalanced seam permeability and it can also increase the volume of seam in which permeability can be increased.

5.2.2. HTSPE Theory Improvements

The theories about HTSPE should be improved by basic theoretical research. For example, coal containing water and gas can probably be considered to be in a three-phase coupled state and the failure criteria and constitutive equations may be different for that kind of system. Mineral compositions, structural systems, and gas adsorption and desorption effects in a coal seam also result in complexity for hydraulic fracturing in underground coal mines. Moreover, physical and mechanical reactions among water, coal, and gas should be understood on a microscopic scale. Taking the action mechanisms of pore pressure gradients as a starting point, the microscopic fracture mechanisms and stress disturbance effects of hydraulic fracturing in coal should be studied intensively.

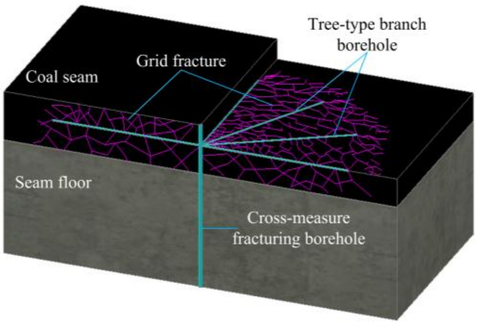

Figure 15. Diagrammatic sketch showing a tree-shaped boreholes fracturing technology.

5.2.3. Directions for Future HTSPE Equipment Development

On-board intelligence and miniaturization may be the trend for HTSPE equipment in the future. Intelligent equipment can be controlled precisely and collect accurate data and miniaturization could contribute to both transportation and installation in underground coal mines.

6. Conclusions

As an important technology to improve the efficiency of gas extraction and to control or prevent gas accidents, HTSPE is well placed to contribute to the coordinated development of coal and gas. This model for coordinated development has been proposed by the Chinese government and will be applied much more widely. Previous and future research will support this proposal and continue to advance the technology and this will rapidly drive the capacity for sci-tech independent innovation in CBM utilization and gas accident prevention in China. HTSPE is progressing day by day, following continued improvements in theories and equipment, and is playing an increasingly important role in coal mining and CBM development.

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