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# Technical Parameters of Hydraulic Punching in a Typical Coal Seam and an Investigation of Outburst Prevention Effect: A Case Study in the Machi Mine, China

Yanpeng Xu · Liguo Wang

**Abstract** The Dengfeng coalfield belongs to the typical "three soft" coal seam and has a high gas content ranging from 10 to 13 $m^3$/t, and the coal seam gas content reaches a maximum 13.69 $m^3$/t. Because of its coal seam occurrence, no protective layer can be mined. The conventional regional pre-pumping measures have several problems. For example, the construction of a pre-pumping borehole is difficult, and it easily causes a coal and gas outburst. The low permeability and rheological characteristics of the coal seam lead to the collapse of the borehole and seriously affects the drainage effect. The influence radius of the drainage borehole is small, which results in a larger quantity of new drilling boreholes and significantly increases the operational cost. Compared to the conventional regional pre-pumping measures, floor roadway hydraulic flushing rapid outburst technology can effectively overcomes these issues. Hydraulic flushing uses water to flush the borehole, and the newly formed fractures and the release of free gas greatly reduce the elastic potential and gas expansion energy of coal and rock, which thus significantly improve the permeability of the coal and improve the coal seam degasification efficiency for outburst risk control. In this paper, a hydraulic punching method is utilized for coal seam stimulation in the Machi mine. Reasonable technical parameters of hydraulic punching were obtained: the water pressure of punching and breaking coal is 8–15 MPa, and the equivalent diameter of the hydraulic punching nozzle should be < 7.47 mm. After the implementation of the hydraulic punching measures, the gas extraction capacity of the coal around the borehole is greatly improved. For 90 days gas extraction after stimulation, the gas content of the 11,061 lane decreased from 8.42–12.12 $m^3$/t to 3.09–5.75 $m^3$/t, relieving pressure and increasing permeability of "three soft" coal and simultaneously eliminating the outburst danger of the coal seam.

**Keywords** Hydraulic punching · "Three soft" coal · Technical parameters · Gas drainage

Y. Xu · L. Wang (✉)
Engineering Research Center of Coal Mine Disaster Prevention and Emergency Rescue, Ministry of Education, Henan Polytechnic University, Jiaozuo 454000, People's Republic of China
e-mail: wangliguofirst@163.com

Y. Xu · L. Wang
Collaborative Innovation Center of Coal Safety Production of Henan Province, Jiaozuo 454000, Henan, People's Republic of China

## 1 Introduction

In China, 97% of the coal mines are underground mining. With the high demand for coal and an increasing underground mining intensity and strength,

the current mining environment in China is complex which is shown by the frequent gas occurrence and the frequent coal mine disasters. Among all coal mine accidents, gas accidents account for 70%–80% and becomes one of the main natural enemies of coal mine safe production. With the active development of national gas controls, the number of gas casualties has gradually declined. In 2009, the mortality rate per millions of tons fell to below 1% for the first time (Fig. 1). However, the situation of mine gas management in China still remains serious. Gas disaster is still an important factor threatening the national energy security, which restricts the development of the national economy. Therefore, strengthening gas extraction technology and realizing highly efficient gas extraction is necessary to prevent and control coal and gas outbursts and ensure the safety of workers' lives. This is also the only way for sustainable development of the coal industry.

Since the first coal and gas outburst occurred in the Iacke mine in Luaray, France, in 1834, coal and gas outbursts have occurred in 22 countries and regions. To prevent their occurrence, the Makiyivka coal mine safety institute proposed outburst prevention measures of unloading grooves around the roadway from 1968 to 1972 (А.ЛсйникоВ et al. 1981). The Makiyivka coal mine safety institute also implemented outburst

prevention measures of hydraulic testing, the effect of hydraulic extrusion, hydraulic loosening, hydraulic flushing and low pressure wet coal measures. After implementing the measures, the gas emission of the mine was reduced, the gas dynamic phenomenon was reduced, and the outburst prevention starts working.

In China, scientific research institutes have performed extensive research on coal and gas outburst prediction and control since 1950 (Chen et al. 1999; Xu and Wang 2011; Xu et al. 2011; Yuan 2016; Xu and Jiang 2017; Aguado and Nicieza 2007). Some outburst prevention techniques, such as pre-discharge drilling, loose blasting, and hydraulic measures, have been studied.

Various research institutes have conducted extensive researches on application of hydraulic measures (Wang et al. 2014; Yuan et al. 2015). Hydraulic measures include coal seam water injection, hydraulic extrusion, hydraulic fracturing, and hydraulic punching.

Coal seam water injection means injecting low pressure water in the coal body by boreholes in front of the face, which increases the moisture content and thus reduce the elastic modulus and compressive strength of the coal. This technique causes coal seam soften and significantly improve the plasticity of the coal seams. The stress concentration peak is pushed to the front of



Fig. 1 National coal mine accidents in 2004–2015
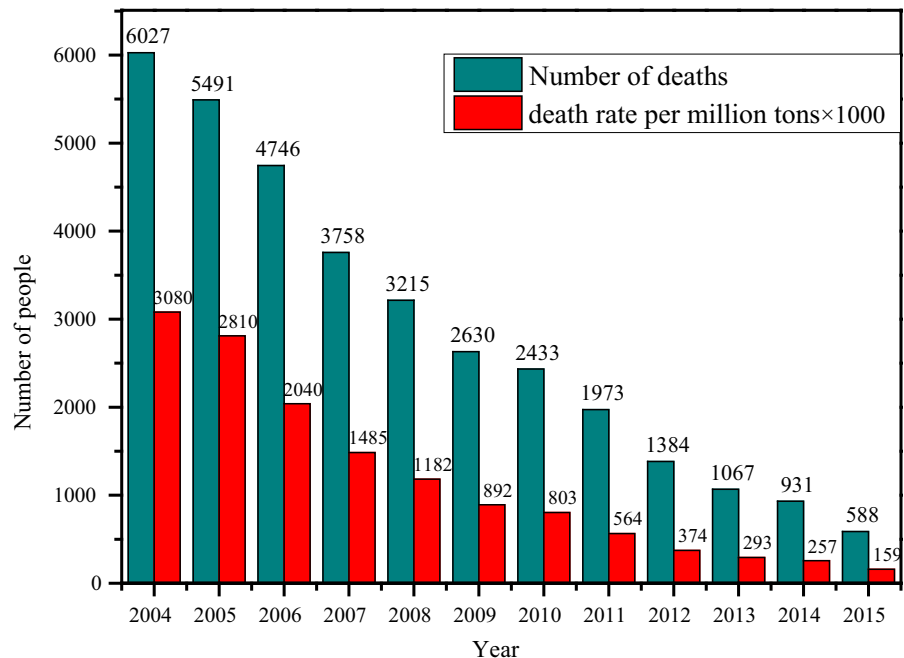
the working face, which expands the pressure relief area and has the potential to reduce or eliminate the outburst danger (Aguado and Nicieza [2007]; Chen and Cheng [2015]; Cheng et al. [2012]).

Hydraulic extrusion means injecting high-pressure water in the coal body by boreholes in front of the face. When the water injection rate exceeds the coal penetration rate, the coal will expand and crack and be pushed to the working face to facilitate the unloading and discharge of gas (Xu [2007], Xu and Qiu [2008]; Wang and Li [2004]).

Hydraulic fracturing is the injection of high-pressure water in the deep coal in the working face. Horizontal and vertical cracks occur in the solid coal from the action of the water pressure. Coal body internal stress is released, which improves coal seam permeability, promotes gas desorption, and increases gas emission and drainage. Finally, the risk of outburst is eliminated (Morales [1992]; Mrak [1992]; Huang et al. [2011]; Li et al. [2015]; Lin et al. [2011]; Liu et al. [2015]).

Hydraulic flushing is conducted under the protection of the rock column using the impact of a high-pressure water jet and the cutting action of the nozzle to flush the borehole. The state of the original stress equilibrium of the coal in the surrounding area is disturbed. The outburst energy is released. A large amount of coal and gas discharges from the drilling water erosion, which makes the coal around the holes fully unload. Coal seam permeability is greatly increased promoting gas desorption and emissions, thereby improving pumping efficiency and eliminating the risk of outburst (Liu et al. [2005]; Li et al. [2011]; Kong et al. [2016]).

Compared with other hydraulic measures, hydraulic punching characteristics do not need very high water pressure (10–20 MPa), but they need to have a certain amount of water to stimulate release. The technology utilizes the impact of drill cutting and a water jet to destroy the balance of the stress and the gas stress in the coal body around the borehole releasing its outstanding potential under artificial control safely and efficiently. The reason is that the rock pillar is a safety barrier and the drilling blowout preventer controls gas. Using hydraulic flushing to induce blowout to reduce gas pressure and increase permeability of the coal seam the amount of coal and gas can be effectively controlled through the blowout prevention device and a hydraulic pump rig. Furthermore, the jet pressure is continuous and a large amount of coal

and gas is discharged from the borehole, which effectively reduces the potential of the outburst and thus ensures the safety in the mining process.

Since the "three soft (soft roof, soft coal and soft floor)" unstable low permeability coal seam roof is unstable, the strength coefficient is small, coal easily spalls, and gas migration and drainage are difficult, gas emission and control technology has been a major difficulty in mine gas control work. The low permeability feature of a "three soft" coal seam is the bottleneck of high efficiency gas extraction, and improving the permeability of the coal seam is the key to solving the problem. In this paper, through the use of advanced hydraulic punching equipment, a process of high efficiency gas extraction technology suitable for a "three soft" coal seam is formed, which achieves "three soft" coal seam pressure relief and permeability increase.

## 2 General Engineering Situation

The Machi mine is a coal mine in China that operates with the outburst potential, which is strictly managed by the government. The mine is located in Henan Province and exhibits complex geological and mining conditions. The mine produces 0.3 million tons of coal annually. There are 21 layers of completely or partially mineable coal seams with a total thickness of 11.72 m in the coalfield. The main mineable coal seam is the $\#2_1$ coal seam, which has an average dip angle of 22°. The thickness of the $\#2_1$ coal seam is 2.05–4.21 m, with an average of 3.65 m. Coal seam $\#2_1$ is prone to outbursts. The gas content is 13.69 $m^3$/t. The gas pressure is 1.1 MPa. The permeability coefficient of the $\#2_1$ coal seam is 0.215–0.723 $m^2$/$MPa^2$ d, which creates difficulties for gas extraction. The coal strata histogram of the Machi mine is shown in Fig. [2].

## 3 Hydraulic Punching System

### 3.1 Selection of Hydraulic Punching Equipment

The hydraulic punching system consists of an emulsion pump station, high-pressure hose, pressure gauge, drilling rig, nozzle, blowout preventer and filter press. The system connection is shown in Fig. [3].

| System | Group | | | Lithology succesion | | Thickness (m) | Petrographic description |
|---|---|---|---|---|---|---|---|
| Q | | | | | | 9.19 | Loess and alluvium |
| Triassic system | Heshanggou group | | | | | 190.00 | Medium grained sandstone |
| | Liujiagou group | | | | | 288.40 | Thin mudstone / Thin sandy mudston |
| Permian System | Shiganfeng group | | | | | 127.35 | Fine sandstone |
| | | | | | | 98.21 | Mudstone and sandy mudstone |
| | | | | | | 73.18 | Sandstone mudstone interbed |
| | | | | | | 75.46 | Coarse feldspar, quartz sandstone |
| | Upper Shihezi group | 9 coal group | | | | 56.00 | Mudstone, sandy mudstone, fine powder, sandstone, interbed |
| | | 8 coal group | | | | 83.00 | Mudstone, sandy mudstone, fine powder, sandstone, interbed |
| | | 7 coal group | | | | 85.00 | Mudstone, sandy mudstone interbedded, from top to bottom containing $7_5$, $7_4$, $7_3$, $7_2$, $7_1$ coal |
| | Lower Shihezi group | 6 coal group | | | | 85.00 | Mudstone and sandy mudstone |
| | | 5 coal group | | | | 79.00 | Mudstone, sandy mudstone and medium fine sandstone, from top to bottom containing $5_5$, $5_4$, $5_3$, $5_2$, $5_1$ coal |
| | | 4 coal group | | | | 73.00 | Mudstone and sandy mudstone, from top to bottom containing $4_7$, $4_6$, $4_5$, $4_3$, $4_2$ coal |
| | | 3 coal group | | | | 68.00 | Mudstone, sandy mudstone, fine sandstone |
| | Shanxi group | 2 coal group | $2_5$ coal | | 0.04 | 70.00 | Mudstone, sandy mudstone, fine sandstone |
| | | | $2_4$ coal | | 0.01 | 76.00 | Mudstone, sandy mudstone, fine medium grained sandstone |
| | | | $2_3$ coal | | 0.01 | 140.00 | Sandy mudstone / Mudstone |
| | | | $2_2$ coal | | 0.51 | | |
| | | | | | 7.12 | | |
| | | | $2_1$ coal | | 5.04 | 14.66 | $2_1$ coal / Mudstone / Sandy mudstone / Fine-grained sandstone |
| | | | | | 9.26 | | |
| | Taiyuan group | 1 coal group | $1_8$ coal | | 0.06 | 19.08 | Sandy mudstone / Mudstone |
| | | | $1_7$ coal | | 0.25 | | |
| | | | $1_6$ coal | | 0.20 | 9.05 | Medium grained sandstone / Siltstone |
| | | | $1_5$ coal | | 0.77 | | |
| | | | $1_4$ coal | | 0.18 | 14.70 | Limestone |
| | | | $1_3$ coal | | 0.78 | | |
| | | | $1_2$ coal | | 0.31 | | |
| | | | $1_1$ coal | | 0.56 | | |

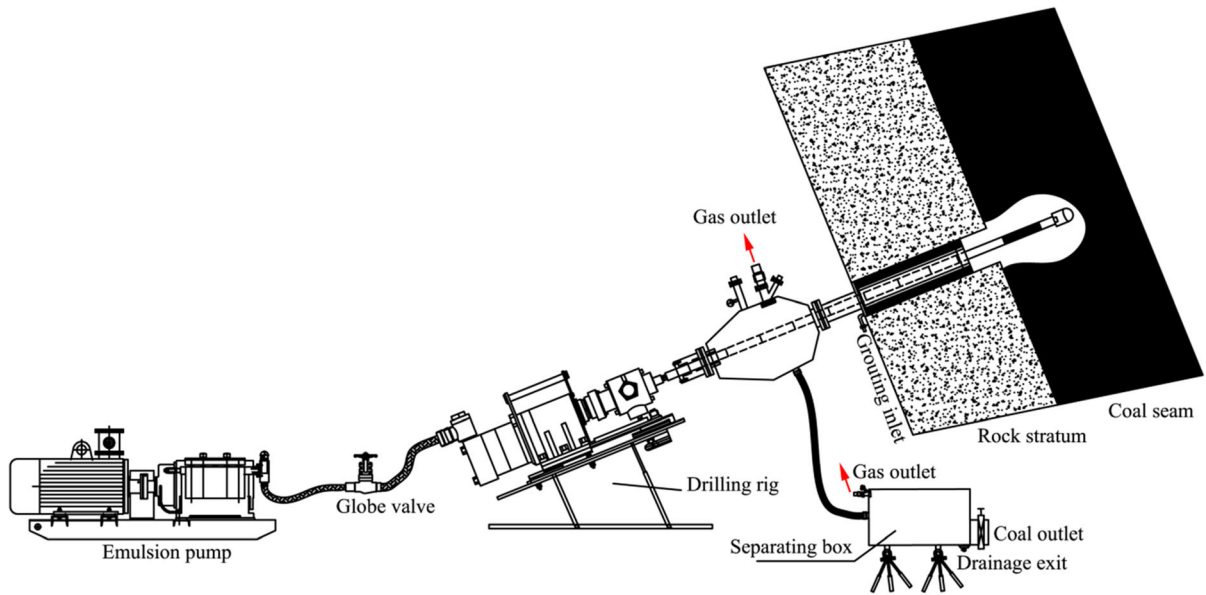Fig. 2 The coal strata histogram of the Machi mine

**Fig. 3** Hydraulic flushing system diagram

### 3.2 Emulsion Pump and Emulsion Tank

The emulsion pump is type BRW315/31.5, its rated pressure is 31.5 MPa, and the rated flow is 315 L/min. The matching emulsion tank is an XR315/25; its rated pressure is 31.5 MPa, rated flow 315 L/min. The specific parameters of the emulsion pump and emulsion box are shown in Table 1.

### 3.3 High-Pressure Hose

High-pressure hose diameter specifications are generally 8 mm, 16 mm, 25 mm, or 32 mm. In the Machi coal mine, the hydraulic punching connecting pipe with an inner diameter of 32 mm and a pressure of 35 MPa is connected with an emulsion pump. The

other end of the hose is connected to the tail end of the 50 mm drill rod by a fast joint and a U type card. At the end of the drill rig, a measuring range of 0-25 MPa high-pressure water metre is installed to monitor the water jet pressure during drilling, and a stop valve is installed beside the pressure gauge.

### 3.4 Hydraulic Punch Nozzle

A modified nozzle is used in the Machi coal mine. The two holes at the top of the scrapped 75 mm drill bit are closed, and the three side drains are retained as the punching bit. The physical drawing is shown in Fig. 4.

**Table 1** Emulsion pump and tank parameters

| BRW315/31.5 emulsion pump | | | |
|---|---|---|---|
| Nominal pressure | 31.5 MPa | Motor power | 200 KW |
| Nominal flow rate | 315 L/min | Motor speed | 1485 r/min |
| Weight | 4800 kg | Boundary dimension | 3100 × 1250 × 1200 mm |
| Manufacturing number | 86–9 | Date of production | April, 2014 |
| XR315/25 emulsion tank | | | |
| Nominal pressure | 31.5 MPa | Nominal flow rate | 315 L/min |
| Nominal capacity | 2500 L | Working medium | Emulsion |
| Manufacturing number | 41–9 | Date of production | April, 2014 |
| Shandong new coal machinery equipment co. LTD | | | |
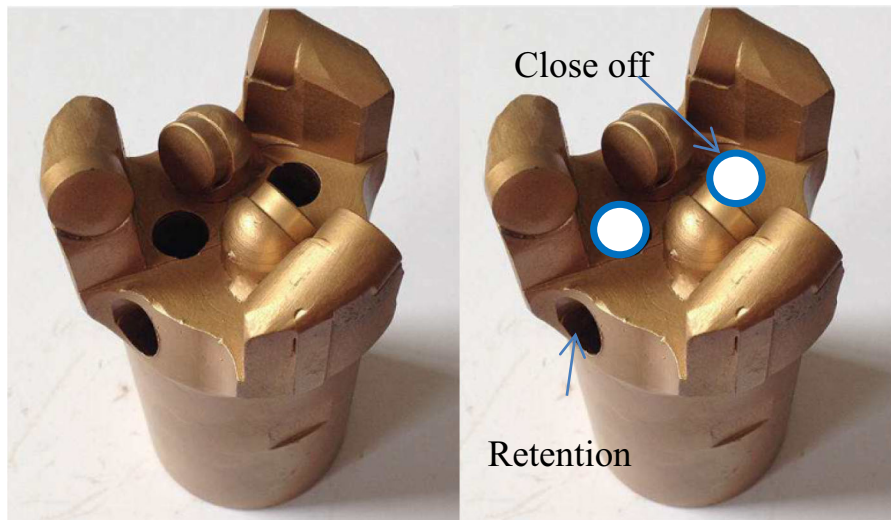
**Fig. 4** Sketch of reconstructed drill bit

### 3.5 Blowout Preventer

In the process of hydraulic punching, a large amount of coal will be thrown out of the borehole, stress will be reduced, and a large amount of gas will be desorbed. With the large amount of coal and water flowing out of the borehole, gas will often exceed the limit. To solve this problem, a blowout preventer is used to route the gas into the extraction pipeline to prevent the gas in the working face from exceeding the standard. The schematic and physical drawings of the blowout preventer are shown in Fig. 5.

The blowout preventer is composed of a four-way valve (steel tubes with diameter of 108 mm), press filter and related connecting pipes. The fronts of four orifices (1 m or so) are fixed with cement in the drilling hole. The left side of the hose is a gas extraction branch where the gas pipeline is connected. The hose on the right is a branch of coal and gas where the press filter is connected. During the hydraulic punching, as soon as the spray gas reaches the orifice, some of the gas is pumped out by the pumping pipe on the left. The remaining gas and coal and water enter the right pipeline and finally enter the press filter to separate coal, gas and water.

### 3.6 Press Filter

The function of a press filter is to filter out the coal and water that are punched out. After filtration, the mixture
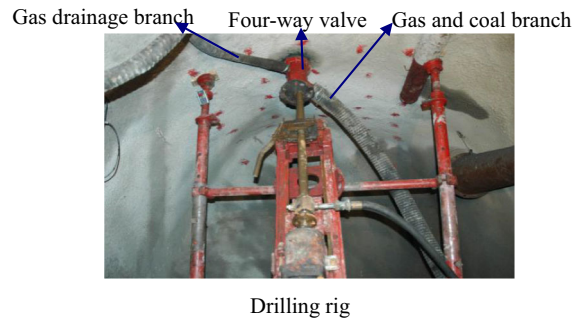


**Fig. 5** Physical map of a blowout preventer

of liquid and solid is separated into lower moisture coal and water that can be recycled.

## 4 Reasonable Technical Parameters of Hydraulic Punching

### 4.1 Calculation of Coal Breaking Water Jet Pressure

It is important to determine the breaking pressure of the water jet to improve the efficiency of the water jet in breaking coal. Many researchers have studied the mechanical characteristics of water and coal in the process of water jet breaking coal (Mu and Wu 2013; Mu and Han 2015).

The damage of coal by the action of a high-pressure water jet and the critical breaking strength was

studied, and the critical crushing strength of coal from the action of a high-pressure water jet was obtained:

$$R_t = Y \left( \frac{\frac{E}{3Y}}{1 - \sqrt{\frac{\sigma_t}{Y}} \frac{1-\mu}{\sqrt{2}}} \right)^{\frac{2}{3}\eta} \tag{1}$$

where $R_t$ is the crushing strength of coal, MPa; $E$ is the elastic modulus of coal, MPa; $Y$ is the compressive strength of coal, MPa; $\sigma_t$ is the tensile strength of coal, MPa; $\mu$ is the Poisson ratio of coal, and $\eta$ is a calculation factor $\eta = 6k/(3 + 4k)$ where $k$ is the compression-shear factor.

The threshold speed of a water jet breaking coal is:

$$v = \sqrt{\frac{\beta R_t}{\rho w}} \tag{2}$$

where $v$ is the threshold speed of a water jet breaking coal, m/s; $\beta$ is the reflection water jet area factor and $\rho_w$ is density of water, kg/m$^3$.

According to the Bernoulli theory of fluid flow, high-pressure water injection pressure is:

$$P = \frac{\rho_w v^2}{2} \tag{3}$$

The mechanical parameters of the #$2_1$ coal seam in the Machi coal mine are shown in Table 2.

When the data in the table are entered into formulas 1, 2, and 3, the critical crushing strength, the threshold velocity and water injection pressure are 6 MPa, 93 m/s and 4.3 MPa for the action of the high-pressure water jet in the Machi coal mine. This is not to say that the jet pressure will burst if it is greater than 4.3 MPa. The reason is that the actual situation at the operation site is very complicated and easily affected by many factors. It is impossible for the practical application to completely agree with the theoretical. Therefore, the hydraulic punching water pressure is set to 8–15 MPa.

## 4.2 Parameter Design of the Hydraulic Punching Nozzle

The nozzle is one of the key parts of hydraulic punching, which changes fluid pressure into kinetic energy. The jet from the nozzle has very high energy and can cut and break the coal. It is important to study the relationship between the nozzle structure and jet flow. The nozzle structure is quite different for different jet applications. A typical nozzle for hydraulic punching is a conical nozzle, as shown in Fig. 6 where L is length of the cylindrical section, β is the contraction angle and $d_0$ is the nozzle outlet diameter

For the conditions of known flow rate $q$ of the emulsion pump station, the pressure P at the nozzle decreases with the increase of nozzle diameter and satisfies the following relation:

$$P = 0.227 \frac{q^2}{\mu^2 d^4} \tag{4}$$

where $P$ is the jet pressure, Mpa, $q$ is the jet flow rate, L/min, $\mu$ is the discharge coefficient of the nozzle and $d$ is the nozzle outlet diameter, mm.
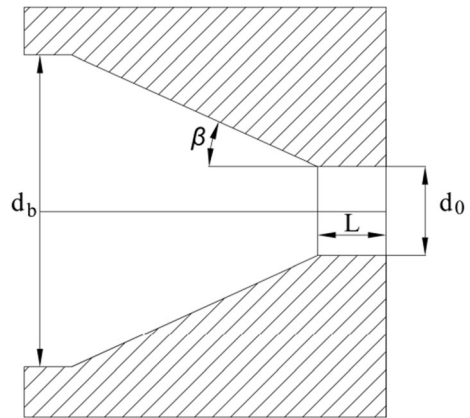


**Fig. 6** Schematic cone nozzle

**Table 2** Machi Coal physical parameters

| Coal | Density/kg/m$^3$ | Elasticity modulus/MPa | Poisson's ratio | Compressive strength/Mpa | T-C ratio | Coefficient of solidity $f$ |
|------|------------------|------------------------|-----------------|--------------------------|-----------|------------------------------|
| #$2_1$ | 1380 | 1500 | 0.3 | 5 | 11 | 0.3 |

The above calculation is only applicable to single nozzles, and hydraulic nozzles often use multiple nozzles; therefore, the nozzle diameter is converted into nozzle equivalent diameter when calculating. The nozzle equivalent diameter can be calculated by the following model:

$$d = \sqrt{d_1^2 + d_2^2 + d_3^2 + \cdots + d_n^2} \qquad (5)$$

where $d$ is the nozzle equivalent diameter, mm, and $d_n$ is the diameter of the nth nozzle, L/min.

The nominal flow rate of the emulsion pump is 315 L/min, and the nozzle flow coefficient is 0.95. The pressure at the nozzle corresponding to the equivalent diameter of the nozzle can be calculated. The calculation results are shown in Fig. 7.

As shown in Fig. 7, when the nozzle equivalent diameter is greater than 8 mm, the jet pressure at the nozzle site is very small and cannot meet the needs of hydraulic punching. If the jet pressure is greater than 8 MPa, the nozzle equivalent diameter should be less than 7.47 mm.

## 4.3 Hydraulic Punching Nozzle and Hydraulic Testing

Prior to the start of the hydraulic punching, the fan should be turned on to an air volume of 350 m³/min. The punched bit is modified with a 75 mm drill bit, the top two holes of the 75 mm bit are totally closed, and the three side drains are retained as the punching bit.
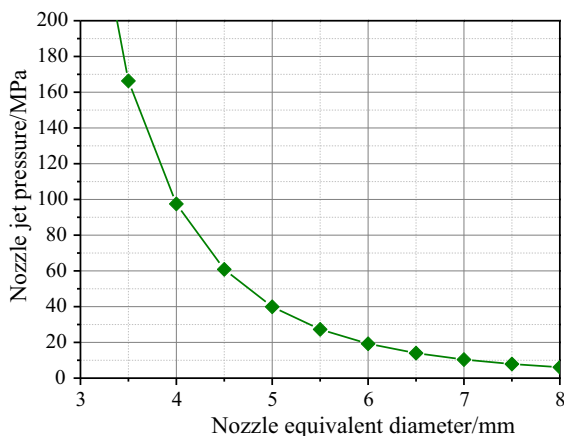


**Fig. 7** Relationship between nozzle equivalent diameter and jet pressure

To ensure the safety of construction, the hydraulic pump pressure is set to 5 MPa first. The drill pipe is wrapped with cotton cloth to prevent water leakage, resulting in lower punch pressure. When the drilling rig starts to rotate, the water inlet is displayed. The pressure gauge shows that the water pressure is 0, and the water in the drilling hole is clear and smooth, indicating that the coal body has not been washed out. When the inlet valve is closed, the water pressure is normal. The analysis shows that the nozzle size is too large ($3 \times \phi$ 5.0 mm, equivalent diameter is 8.66 mm). A nozzle of this size causes the water pressure of piercing to be too small to effectively cut coal. The nozzle should be reformed and $2 \times \phi$ 5.0 mm nozzles (equivalent diameter 7.07 mm) should be used for punching.

With the hydraulic pump outlet pressure is set to 5 MPa, the rig can be turned on and the pressure gauge should be observed. The water pressure gauge shows the water pressure is slightly lower at 4.5 MPa; drilling with black water outflow shows that coal has started crushing under the high-pressure water jet and is flowing out with the water, but the quantity of coal is not too large, and the effect is not ideal. In the process, there is no abnormal gas concentration in the return current and the gas probe shows a gas concentration of approximately 0.04%.

To further enhance the punching effect, the hydraulic pump pressure is set to 10 MPa. At this pressure, when the rig rotates, the water pressure at the pump body is 8 MPa. The output of coal increases rapidly, and turbid and black viscous water flows out of the hole, indicating that the coal in the borehole has been largely broken.

The hydraulic pressure of the hydraulic pump is increased to 20 MPa because a large amount of coal slime is gushing out, the drilling hole is a small 113 mm hole, and the water flow is no longer continuous indicating interstitial ejection. In this process, the drilling rig will not stop the water supply. When the water fills holes in the coal, it is possible to press out more viscous coal water mixture in the rock hole.

After test and investigation, the punching effect is the best using $2 \times \phi$ 5.0 mm nozzles (equivalent diameter of 7.07 mm) for punching and hydraulic punching pump pressure at 15-20 MPa.

# 5 Application Test of Rational Parameters of Hydraulic Punching

## 5.1 Drilling Arrangement

A drilling field (4 × 4 × 3.6 m) is arranged every 30 m at the gas drainage roadway of the floor. The diameter of the drilling hole is 113 mm, the distance between the drill end is 6 m, and the drilling hole enters the roof of the $2_1$ coal seam at 0.5 m. The 11,061 sub roadway design has 7 rows of shield drilling, and the protection scope is 36 m, which can ensure the safety of tunnelling, as shown in Fig. 8.

In each row of drilling boreholes at each field, hydraulic flushing was carried out with the arrangement of odd and even interleaving between the upper and lower two rows. This can meet the needs of gas drainage and can guarantee no blank region. The arrangement and influence range of hydraulic punching holes are shown in Fig. 9.

## 5.2 Hydraulic Punching Process

At the punching position, a 113 mm drill hole is constructed. The drill hole should enter the roof of the coal seam. Before punching, it is necessary to ensure that the air flow in the tunnel is enough, so that the all air can be ventilated with negative pressure.

The drill pipe is pulled out and the refitted cutter is changed (the modified 75 mm bit is welded to the 50 mm drill pipe). The pipe should be sealed tightly with cotton yarn and sent to the interface of coal and rock.

When the high-pressure water is connected, the emulsion pump is opened with the water pressure (pressure should not be too high). When the water pressure is increased slowly to the maximum (no more than 20 MPa), turn on the high-pressure water valve and start pumping water into the borehole. When the orifice is out of water, start the drilling machine and start punching.

When punching the first drill rod, it should be continued for a long time until clear water is discharged from the borehole. At this point, the next drill pipe can be installed. When the rod is installed, punching should be stopped, the high-pressure water valve should be closed, and the relief valve should be opened. When the pressure in the drill pipe is completely unloaded, the connecting rod is started. When attaching the connecting rod, use cotton yarn to close the joint of the drill pipe gap to prevent leakage. Repeat the punching operation after the staff reaches the safe position.

In the process of punching, make sure the flow is smooth. If the drilling hole is blocked and the water flow is not smooth, it should be stopped immediately, and the drill pipe withdrawn and pushed back and forth several times. When the flow is smooth, it should be pushed forward slowly.

If the above method still cannot make water flow smoothly, immediately stop pushing, close the high-pressure water valve, and open the relief valve. When the pressure in the drill pipe is completely unloaded,
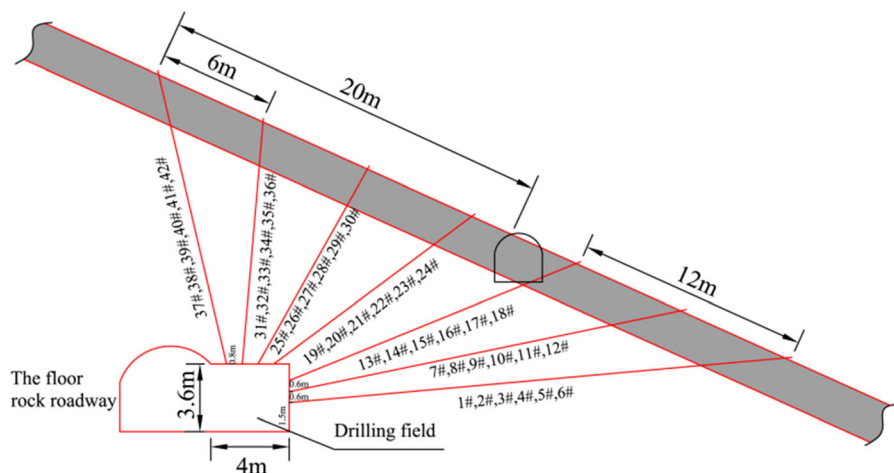


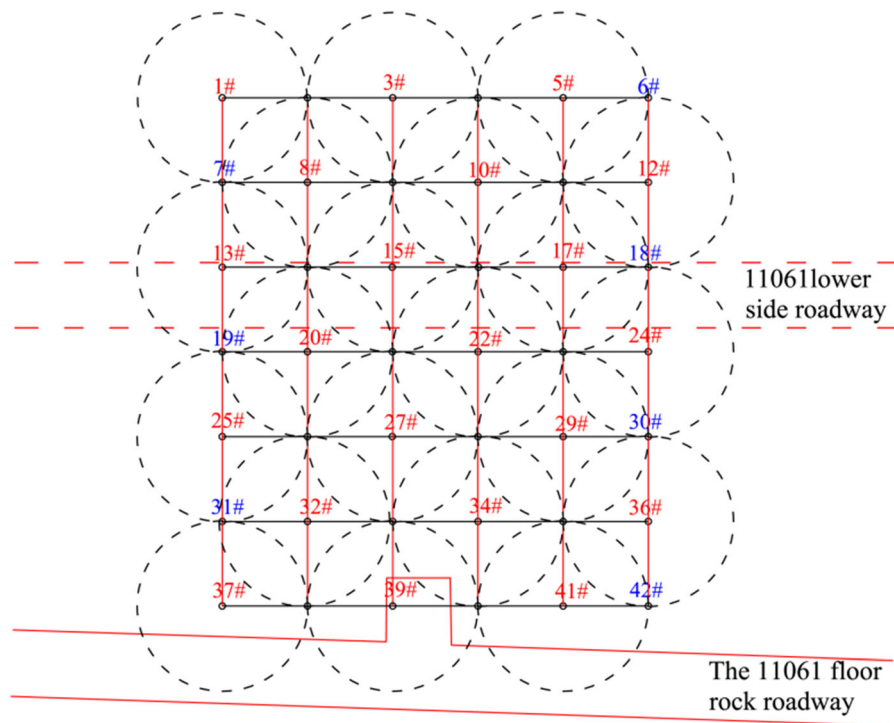**Fig. 8** Profile of cross drill arrangement

**Fig. 9** The layout and influence range of hydraulic punching

exit 3–5 pipe, reconnect the high-pressure water supply to the borehole until the water flows smoothly within the borehole.

When the distance between the cutter and the roof is no more than 0.5 m, the water in the borehole is clear and the punching of hole is finished.

The schematic diagram of the hydraulic punching process is shown in Fig. 10.

5.3 Pressure Relief Gas Extraction

High-pressure water cuts and denudes coal body continuously, which results in the breakage of the coal body and gradually forms a large-scale hydraulic cutting hole. At the same time, the coal body around the hole moves towards the direction of the punched holes significantly, resulting in the expansion deformation of the coal body and the displacement between the roof and floor. The in situ stress decreases, the coal seam is fully decompressed and the fissures increase, which greatly increases the permeability of the coal seam and promotes gas desorption and emission.

When water is near the micro-pore, the injection pressure is almost exhausted, and the capillary force is gradually enhanced. Water enters into the micro-pore of coal body by capillary force and displaces the adsorbed gas by competitive adsorption. With the continuous driving of capillary force, the water level flows continuously, and the displaced gas is gradually driven to the fracture system. The hydraulic punching and pressure relief gas extraction are shown in Figs. 11, 12.

6 Results and Discussion

6.1 Hydraulic Punching Out the Amount of Coal and Gas

Hydraulic punching can produce a large amount of coal and gas, and drilling out of the coal seam directly affects the punching effect. During the hydraulic punching process at the bottom pumping roadway of 11,061, the amount of punching out coal of each drill field is tracked, as shown in Table 3. The average punching out amount of coal is 0.68–1.0 t/m. The ratio of the coal output to the coal control range is 0.86% – 1.42%. The thicker the coal seam is, the better the

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┌─────────────────────────────────┐
│      Wind, water and electrical  │
│       system connections         │
└─────────────────────────────────┘
                │
                ▼
┌─────────────────────────────────┐       ┌──────────────────────┐
│ Drilling rock holes with 113mm bit │─────▶│   Retreat drilling   │
└─────────────────────────────────┘       └──────────────────────┘
          │                │                          │
          ▼                ▼                          ▼
┌────────────────────────┐  ┌─────────────────────────────────────┐
│ Installing blowout preventer │  │ Connecting gas extraction pipeline │
└────────────────────────┘  └─────────────────────────────────────┘
                │                        │
                └──────────┬─────────────┘
                           ▼
┌─────────────────────────────────────────────┐
│      Penetrate the coal seam with 94mm bit   │
└─────────────────────────────────────────────┘
          │                        │
          ▼                        ▼
┌─────────────────────┐  ┌─────────────────────────────────┐
│ Turn on the emulsion pump │─▶│ Determination of gas parameters │
└─────────────────────┘  │     in extraction boreholes     │
          │               └─────────────────────────────────┘
          ▼
┌──────────────────────────────────────────────────┐
│  Coal and water are discharged into the buffer box │◀─
└──────────────────────────────────────────────────┘
                    │
                    ▼
┌────────┐    ┌─────────────────────┐    ┌────────┐
│  Coal  │◀───│ Starting filter press │───▶│ Water  │
└────────┘    └─────────────────────┘    └────────┘
                    │
                    ▼
┌──────────────────────────────────────┐
│  Finish hydraulic flushing, stop pumping │
└──────────────────────────────────────┘
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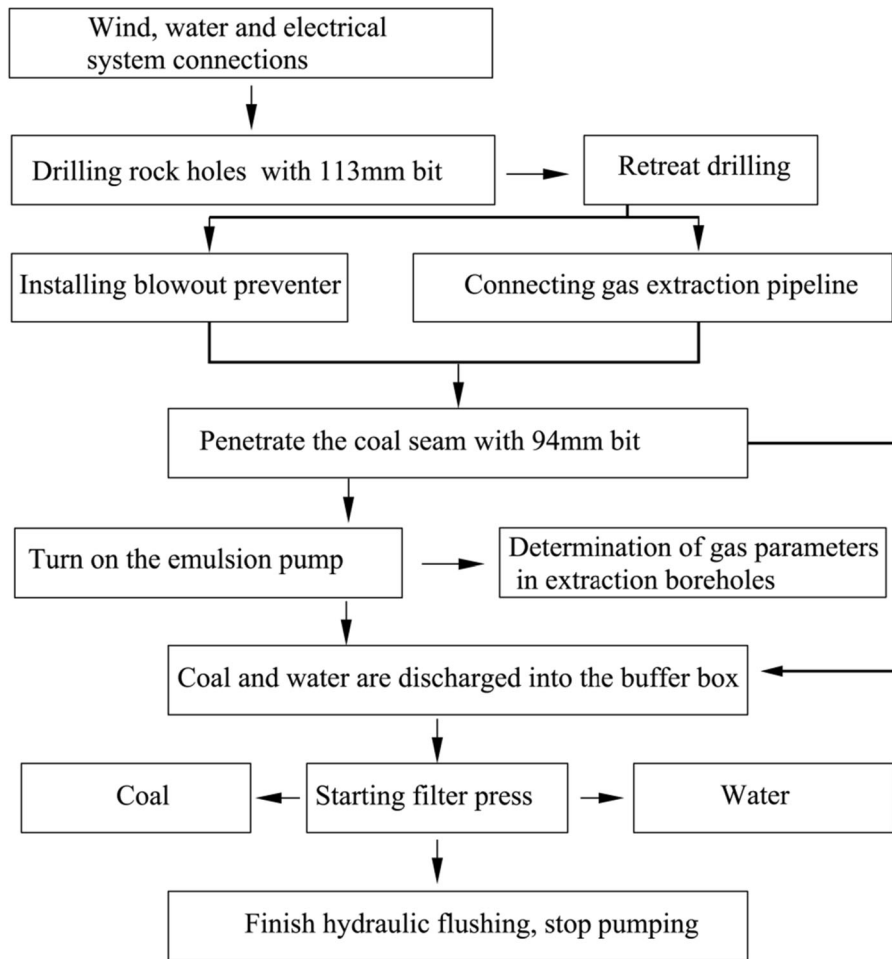
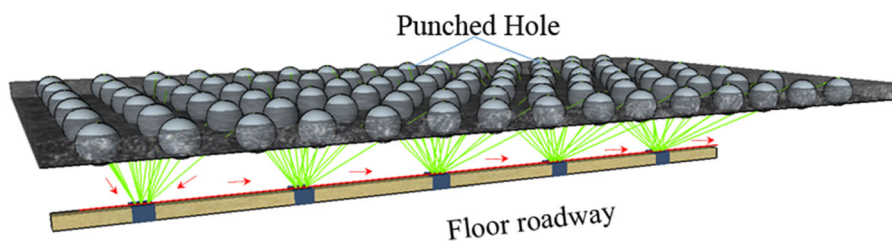Fig. 10 Sketch map of hydraulic punching process



Fig. 11 Sketch map of hydraulic punching

punching effect is, and the more coal is produced on average.

During the #27 drilling hole at #9 drill field, the wind exhaust gas concentration at the bottom pumping roadway of 11,061 is shown in Fig. 13. The punching begins at 16:30 and the punching ends at 20:30. The coal hole length of the #27 hole is 8 m, and the total coal output is 7 t. At the 11,061 bottom pumping lane, the normal air volume is 350 $m^3$/min. Before punching, air gas concentration is 0.02%, during the punching process, the air gas concentration increased up to 0.16%. Through calculation, it can be concluded that from 16:00 to 24:00, the exhaust gas increment is 152.8 $m^3$, and the gas emission is 21.8 $m^3$/t.
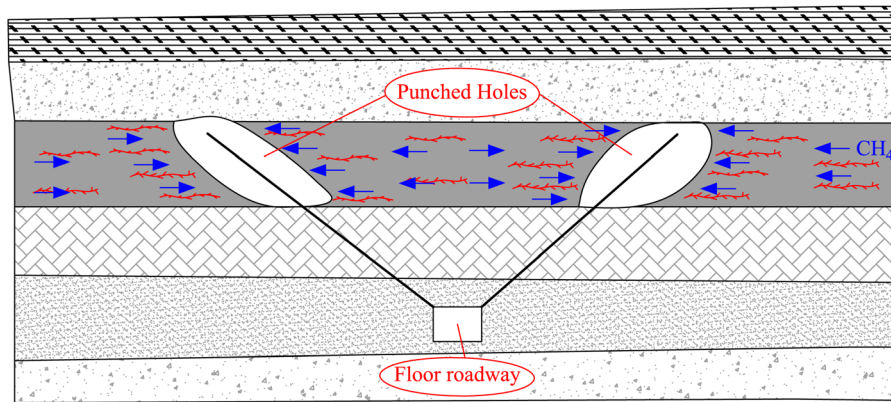
**Fig. 12** Sketch map of pressure relief gas extraction

**Table 3** Statistics of coal output from each drilling field

| Drilling field | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 |
|---|---|---|---|---|---|---|---|---|
| (a) Punching out the amount of coal in the #2–#9 drill fields | | | | | | | | |
| The average coal thickness/m | 2 | 2 | 2 | 1.6 | 2 | 3.6 | 5 | 5.5 |
| Number of punching holes | 21 | 21 | 21 | 21 | 21 | 23 | 21 | 20 |
| Punch out the total amount of coal/t | 39.5 | 38.7 | 34.6 | 32.8 | 38 | 81 | 119 | 128 |
| Proportion of coal to coal of control area/% | 1.17 | 1.15 | 1.02 | 1.21 | 1.12 | 1.33 | 1.41 | 1.38 |
| Length of coal hole/m | 58.3 | 56.4 | 39.6 | 32.8 | 52.4 | 112.4 | 143 | 158.4 |
| Average single hole coal output/t | 1.88 | 1.84 | 1.65 | 1.56 | 1.81 | 3.52 | 5.67 | 6.40 |
| The average amount of coal per m/t | 0.68 | 0.69 | 0.87 | 1.00 | 0.73 | 0.72 | 0.83 | 0.81 |

| Drilling field | #10 | #11 | #12 | #13 | #14 | #15 | #16 | #17 | #18 |
|---|---|---|---|---|---|---|---|---|---|
| (b) Punching out the amount of coal in the #10–18 drill fields | | | | | | | | | |
| The average coal thickness/m | 5.5 | 5.5 | 4 | 4 | 3 | 3.6 | 4 | 4 | 4 |
| Number of punching holes | 19 | 22 | 20 | 23 | 18 | 21 | 20 | 16 | 12 |
| Punch out the total amount of coal/t | 122 | 120 | 87 | 80 | 61.5 | 72.7 | 96 | 68.7 | 58 |
| Proportion of coal to coal of control area/% | 1.31 | 1.29 | 1.29 | 1.18 | 1.21 | 1.20 | 1.42 | 1.02 | 0.86 |
| Length of coal hole/m | 160 | 149.6 | 115.2 | 114.4 | 83.8 | 104.4 | 104 | 86.4 | 74.4 |
| Average single hole coal output/t | 6.42 | 5.45 | 4.35 | 3.48 | 3.42 | 3.46 | 4.80 | 4.29 | 4.83 |
| The average amount of coal per m/t | 0.76 | 0.80 | 0.76 | 0.70 | 0.73 | 0.70 | 0.92 | 0.80 | 0.78 |

## 6.2 The Hole Diameter Changes of the Punching Hole

Before hydraulic punching, the pore size of the coal hole is 113 mm. After a large amount of coal is washed out, a large cavity is formed within the coal hole section. For the convenience of this study, we will simplify the actual problem assuming that the amount of punching coal in each metre is equal. In this way, the coal output by hydraulic punching of a single hole can be replaced by the punching coal output per metre. The equivalent aperture $d_x$ of hydraulic punching can be expressed in the following form:

$$\frac{m}{\gamma} + \pi \left(\frac{d_0}{2}\right)^2 l = \pi \left(\frac{d_x}{2}\right)^2 l \qquad (6)$$

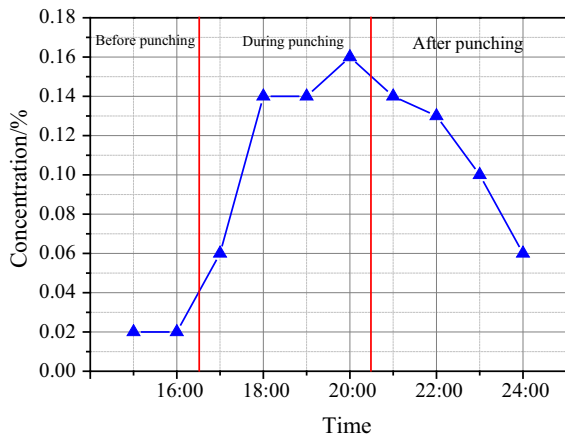$$d_x = 2\sqrt{\left(\frac{d_0}{2}\right)^2 + \frac{m}{\pi \gamma l}} \qquad (7)$$

**Fig. 13** Gas concentration in the 11,061 bottom pumping roadway while punching

where $m$ is the coal output from hydraulic punching, t; $\gamma$ is the apparent density of coal, t/m$^3$; the apparent density of the coal in the Machi coal mine is 1.38 t/m$^3$; $d_0$ is bore hole diameter before punching, m; and $l$ is the length of coal by hydraulic punching, m.

From formula (7), the equivalent pore size of hydraulic punching can be obtained, as shown in Table 4.

From Table 4, the maximum pore diameter after hydraulic punching is 967 mm, and the expansion factor is 8.56. The minimum pore size is 794 mm, and the expansion factor is 7.03. Direct construction of large diameter drilling is difficult and may cause coal

and gas outburst. The formation of the large diameter borehole after punching can expand the range of pressure relief, which transfers the stress concentration area around the borehole to the deep part of the coal seam. A wider range of gas can be desorbed because of the stress drop, which lays the foundation for the better extraction of gas.

### 6.3 Analysis of Coal Seam Permeability Influenced by Coal Quantity

The permeability coefficient of a coal seam is one of the important parameters that determines the difficulty of gas flowing in the coal seam, and it is also one of the important factors that decide the effect of pumping. Gas pressure and crustal stress are important factors affecting coal seam permeability. Generally, the greater the gas pressure is, the higher the crustal stress is and the softer the coal quality is. The worse the permeability is, the greater the difficulty of gas extraction. When the coal seam is fully relieved, the permeability of the coal seam is significantly improved with a high permeability coefficient. Therefore, after hydraulic punching, the change of coal seam permeability in the influence range of hydraulic punching has been investigated.

The permeability expression formula for drilling out the coal quantity was deduced (Zhou et al. 2011):

$$k = k_0 \left[ 1 + \frac{V_1}{(S \times H - V_1) \cdot n_0} \right]^3 \tag{8}$$

**Table 4** Expansion of the hole diameter of the hydraulic punching hole

| Drill field | | #2 | #3 | #4 | #5 | #6 | #7 | #8 | #9 |
|---|---|---|---|---|---|---|---|---|---|
| (a) Expansion of the hole diameter of the hydraulic punching hole for the #2–9 drill fields | | | | | | | | | |
| The original bore diameter/mm | | 113 | 113 | 113 | 113 | 113 | 113 | 113 | 113 |
| The average amount of coal per m/t | | 0.67 | 0.69 | 0.87 | 1.00 | 0.73 | 0.72 | 0.83 | 0.81 |
| Average pore diameter after punch/mm | | 794 | 806 | 903 | 967 | 828 | 823 | 882 | 872 |
| Aperture expansion coefficient | | 7.03 | 7.13 | 7.99 | 8.56 | 7.33 | 7.28 | 7.81 | 7.72 |
| Drill field | #10 | #11 | #12 | #13 | #14 | #15 | #16 | #17 | #18 |
| (b) Expansion of the hole diameter of the hydraulic punching hole for the #10–18 drill fields | | | | | | | | | |
| The original bore diameter/mm | 113 | 113 | 113 | 113 | 113 | 113 | 113 | 113 | 113 |
| The average amount of coal per m/t | 0.76 | 0.80 | 0.76 | 0.70 | 0.73 | 0.70 | 0.92 | 0.80 | 0.78 |
| Average pore diameter after punch/mm | 845 | 867 | 845 | 812 | 829 | 812 | 928 | 867 | 856 |
| Aperture expansion coefficient | 7.48 | 7.67 | 7.48 | 7.18 | 7.33 | 7.18 | 8.22 | 7.67 | 7.58 |

where $k$ is the permeability of coal seam, mD; $k_0$ is the original coal seam permeability, mD; $V_1$ is the volume of coal ejected by drilling, m$^3$; $S$ is the area of the coal body controlled by the drilling group, m$^2$; $H$ is coal seam thickness, m; and $n_0$ is porosity of the original coal seam, $n_0 = 3\%$.

From the data in Tables 3, 4, we can obtain the change of coal permeability in the control range of the 11,061 bottom pumping roadway, as shown in Fig. 14.

The control range of each drill field crossing hole is the same. Therefore, the larger the coal volume is, the larger the expansion of the remaining coal is and the greater the permeability is. The ratio of the coal output to the coal in the control range is 0.86%–1.42% for each drill field. The #16 drilling field has the largest proportion, reaching 1.42%. Therefore, the maximum permeability was increased, and the permeability was increased by 195 times. In the #18 drill field, 12 boreholes were washed out, the washed out coal relative to the total amount of the control range coal is the least, only 0.86%, and the permeability increases minimally, by 58 times.

The permeability of the control range coal of 17 drill fields increases by 131 times on average. According to the original permeability coefficient (0.2–0.7 m$^2$/MPa$^2$ d), the permeability coefficient of the coal seam after drilling is expanded to 26.2–91.7 m$^2$/MPa$^2$ d, which reaches the degree of easy extraction.
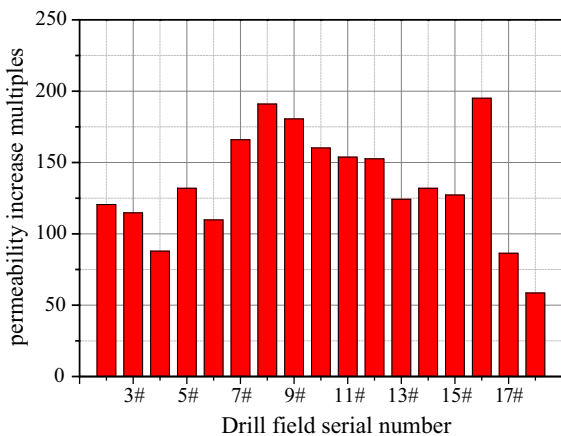
## 6.4 Investigation of Hydraulic Punching Effect

### 6.4.1 Investigation of Gas Extraction Efficiency

The No. 8 drill field was used for testing. First, the #9, 14, 16 and 21 inspection holes were constructed, each hole entering the roof of the #$2_1$ coal seam at 0.5 m. After drilling, the boreholes were connected to the drainage line for extraction and the borehole gas flow is measured. The spacing between the inspected holes is 5–8 m; the position relation diagram is shown in Fig. 15. After pumping for 10 d, the No. 15 borehole was constructed, and hydraulic punching measures were carried out. The gas extraction of 4 inspection holes was measured and recorded. The data are shown in Fig. 16.
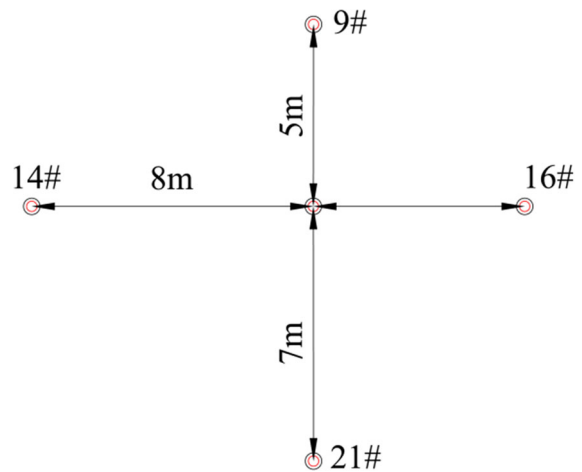
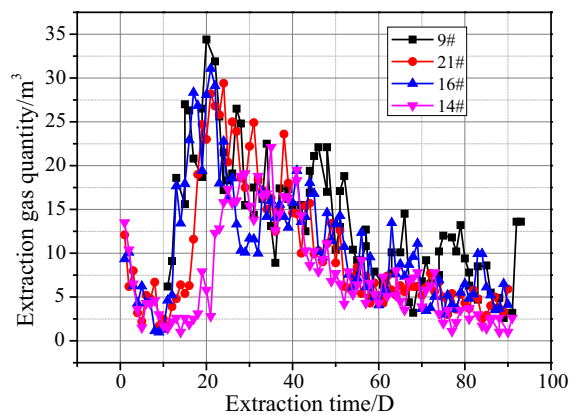**Fig. 15** Borehole inspection layout

**Fig. 14** The permeability increase multiple in the control range of each drill hole group

**Fig. 16** Gas extraction quantity of four drilling

**Table 5** 11,061 sub roadway gas content test results

| Serial number | Sampling position | Residual gas content/m³/t |
|---|---|---|
| 1 | East of the 11,061 sub roadway 43 m | 4.24 |
| 2 | East of the 11,061 sub roadway 116 m | 5.43 |
| 3 | East of the 11,061 sub roadway 182 m | 3.09 |
| 4 | East of the 11,061 sub roadway 265 m | 5.75 |
| 5 | East of the 11,061 sub roadway 329 m | 4.15 |
| 6 | East of the 11,061 sub roadway 402 m | 4.59 |
| 7 | East of the 11061 sub roadway 480 m | 5.58 |

As seen from Fig. 14, after the hydraulic punching measure was implemented, the No. 9 and No. 16 boreholes were affected on the same day and the gas extraction purity increased to a certain extent. The No. 21 borehole was affected on the sixth day after the implementation of the punching action, and the No. 14 borehole was affected on the eighth day. The influence of the hydraulic drilling method on the 4 inspection holes greatly improved the gas pumping capacity. The attenuation rate of gas extraction is greatly reduced before hydraulic punching.

For drill holes at 5 m from the punching hole, the average extraction energy before punching is 6.01 m³/d, the net extraction amount after punching is up to 13.47 m³/d, and the pumping capacity has been increased by 2.24 times. For drill holes at 6 m from the punching hole, the average extraction energy before punching is 5.00 m³/d, the net extraction amount after punching is up to 11.56 m³/d, and the pumping capacity has been increased by 2.31 times. For drill holes at 7 m from the punching hole, the average extraction energy before punching is 5.23 m³/d, and the net extraction amount after punching is up to 10.73 m³/d, and the pumping capacity has been increased by 2.05 times. For drill holes at 8 m from the punching hole, the average extraction energy before punching is 5.31 m³/d, the net extraction amount after punching is up to 7.84 m³/d, and the pumping capacity has been increased by 1.48 times.

### 6.4.2 Investigation of the Effect of Eliminating Outburst Danger

When the pre-pumping coal seam gas measure is adopted to prevent coal and gas outburst, the residual gas pressure or the residual gas content or validated indicators and methods should be used as the main index to test the effect of pre-pumping. If the residual pressure of the coal seam is < 0.74 MPa or the residual gas content is < 8 m³/t, the pre-pumping area has no coal and gas outburst danger. Otherwise, there is danger of coal and gas outburst, and the effect of pre-pumping is not valid (Detailed Rules for Prevention and Control of Coal and Gas Outburst, 2019).

In the 11,061 sub roadway, the gas content of raw coal is 8.42–12.12 m³/t. After punching and pumping 90 d, the outburst prevention measures were checked, the residual gas content is reduced to 3.09–5.75 m³/t, as shown in Table 5, the outburst danger of the working face has been eliminated.

## 7 Conclusion

1. This work studied the reasonable technical parameters of hydraulic punching by mathematical calculation. The water pressure of punching and breaking coal is 8–15 MPa, and the equivalent diameter of the hydraulic punching nozzle should be < 7.47 mm. The selection of hydraulic punching equipment is determined.
2. The change of borehole diameter and the amount of coal and gas punching were analysed. By the mathematical method, the gas permeability of the coal increased by 131 times on average after hydraulic punching.
3. After the hydraulic punching measures are implemented, the gas extraction capacity of the coal around the hole is greatly improved. After punching and pumping 90 d, the gas content of the 11,061 sub roadways is reduced from 8.42–12.12 m³/t to 3.09–5.75 m³/t.

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