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A Novel Method for Borehole Blockage Removal and Experimental Study on a Hydraulic Self-Propelled Nozzle in Underground Coal Mines

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Abstract: When coal bed methane (CBM) drainage boreholes cross fractured, soft, or water-swelling strata, they collapse and block frequently. Borehole blockages result in a rapid decrease in CBM extraction ability, which leads to a reduction in CBM output and threatens coal mine safety production. To solve these problems, a novel method that uses a self-propelled water-jet nozzle to dredge blocked boreholes in coal seams has been proposed on the basis of the existing technology. Based on a theoretical analysis of the reason for borehole caving and the theory of blockage removal, we optimized the nozzle inlet pressure and selected an appropriate high-pressure resin pipe. A field experiment on the blockage removal of blocked CBM drainage boreholes using the proposed method was run in the Fengchun coal mine, Qijiang, Chongqing, southwest China. In this field trial, the time spent to unblock a borehole varied between 18.52 and 34.98 min, which is much shorter than using a drilling rig. After blockage removal, the average pure volume of the methane drainage of a single borehole was increased from 0.03 L/min to ~1.91–7.30 L/min, and the methane drainage concentration of a single borehole increased from 5% to ~44%–85%. The extraction effect increased significantly.

Keywords: coal bed methane (CBM); blocked boreholes; self-propelled nozzle; high-pressure water jet

1. Introduction

Coal bed methane (CBM) is a type of mixed gas, which is composed mainly of methane and is contained in coal seams. CBM extraction can prevent gas disasters in underground mines and, compared with coal, CBM provides unconventional clean energy with a higher caloric value. As an emerging clean energy, abundant CBM has become a potential and reliable gas source worldwide in recent years [1,2].

In China, rapid developments in CBM technology can relieve pressures of natural gas shortages safely and reliably, improve China's energy security situation and coal mine production conditions, and contribute to reducing greenhouse gas emissions [3,4]. Figure 1 shows the Chinese CBM production in recent years.

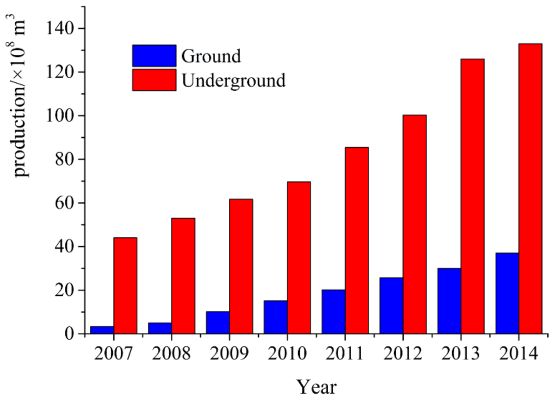

Figure 1. Chinese coal bed methane (CBM) production in recent years.

There has been an increasing trend in Chinese CBM production in recent years. CBM extraction proceeds mainly underground. In China, the main measure of CBM extraction is by drilling cross-drainage boreholes at floor roadways in highly gassy coal seams [5,6]. During CBM drainage, boreholes collapse easily in fractured, soft, or water-swelling strata, which is a major problem [7,8]. Reasons for the collapse and blocking include the fact that borehole instability damage is caused by excavation and mining. Roadway drainage and borehole drilling lead to crevices in coal and rock or even crushed rock that decreases the borehole stability [9]. After borehole formation, new fractures and original fractures extend gradually until they penetrate into each other under the combined action of a geostress field and a high gas pressure gradient, which results in instability and borehole wall destruction, including borehole blocking [10]. On the other hand, highly gassy Chinese coal seams usually exhibit poor physical properties, such as low intensity, low permeability (which increases the extraction time), massive fractures, and great depth [11,12]. Consequently, collapsed coal blocks gas-flow channels and induces several gas drainage problems, including a low gas concentration and flow, and poor drainage results. This behavior also poses a safety threat in coal mine production [13].

Statistics on CBM drainage borehole blocking conditions in underground Chinese coal mines indicate that the average blocking rate is 27%. In some districts in southern China, the blocking rate reaches 68%, because of the soft coal and rock strata. Little research exists on the large number of collapsed and blocked borehole treatments conducted in underground mines. Drilling is conducted mainly by using an in-situ power drill, which exhibits many problems. These problems include: (1) a high cost; (2) it is difficult to match the original borehole direction using a power drill; (3) the borehole drilling rate is low; (4) removing drills is time-consuming; and (5) boreholes must be sealed once the drills have been removed. Anchor rods can also be used to dredge blocked boreholes artificially but only for a particular size range, and so their use has a low success rate.

Water jet drilling is a new technology developed in recent decades. From 1965 to 1968, the initial high pressure water jet drilling test was conducted at the University of Missouri Laura. In 1972, summers researched the capacity of crushing soft and hard rock through cutting sedimentary rock [14]. Before and after the 1980s, the United States carried out the research of radial horizontal well drilling technology, and drilled multiple branching drill holes over 30m to extract the shallow heavy oil [15]. In the last over 20 years, the radial horizontal well technology was developed rapidly and implemented in different countries [16–18]. Some scholars applied radial horizontal well drilling technology which is derived from oil system to the gas drainage boreholes repairing [19], it achieved some success, but there are still some problems. Primarily, the line of drilling equipment is high-pressure oil pipe with high hardness which is difficult to control the drilling direction, and high-pressure oil pipe has a short service life; in addition, the drilling plugging structure is very complex, and the drilling speed changes in a large range, which causes the drilling speed of high-pressure oil pipe is difficult to control; finally, the equipment is large, and it is difficult to adapt to the confined space in underground coal mines.

To solve borehole blocking problems in fractured, soft, or water swelling strata during CBM drainage, a novel method that uses a self-propelled water jet drilling nozzle to clean the borehole has been proposed. Compared with conventional solutions, the technique uses a high-pressure water jet to remove blockages from CBM drainage boreholes in underground mines and exhibits many advantages, such as minimal drill abrasion, no friction or sparking, a high drilling efficiency, and the ability to clear boreholes of large diameter and small broken coal or rock debris of a small particle size [20–22]. Compared with similar technologies, this technique uses a lighter, smaller, and simpler device. The high-pressure resin pipe has a certain flexibility that can refrain from pipe sticking phenomenon and ensure the depth and work efficiency. The self-propelled water jet drilling nozzle can use the recoil force of backward jets that has a greater thrust, so we do not need to provide any additional power to the self-propelled water jet drilling nozzle during drilling process. Meanwhile, backward jets contribute to slag discharging, preventing blockage. In addition, the self-propelled water jet drilling nozzle can drill in original direction [23].

In this study, a field experiment in the Fengchun coal mine, Qijiang, Chongqing, China, was designed to prove the feasibility of this method.

2. Analysis of Borehole Collapse

Borehole excavation can lead to changes in stress state and stress distribution in coal and rock mass that surrounds a borehole. When the coal and rock stress exceeds the yield strength, the rounding areas are converted to plastic zones, and massive fractures are formed in the coal and rock mass in a range of plastic zones. The plastic zone radius can be calculated from Equation (1) [24,25]:

$$R_p = r_a \left(\frac{2}{k+1} \frac{p_0 + qk_p}{p_i + qk_p} \right)^{K_p} \tag{1}$$

where r_a is the borehole radius (m), p_0 is the confining pressure of the borehole (Pa), $K = (1 + \sin\varphi) / (1 - \sin\varphi)$, where φ is the internal friction angle of rock (°), $K_p = 1/(K-1)$, $q = 2c\sqrt{K}$, where c is the rock cohesion.

After borehole formation, under the combined action of a high ground stress and a high gas pressure gradient, new and existing fractures in the borehole wall keep extending until they interpenetrate. This breaks the coal and rock further and results in the formation of a crushed zone in the coal and rock mass surrounding the borehole. Cohesion decreases and as a result, the borehole deforms easily and collapses when the effective radial force on the cell coal block exceeds its cohesion and frictional resistance [26].

CBM drainage boreholes are usually cross-measure boreholes, and most of the collapse and blockages occur in layers of highly gassy and soft coal seam, weak walls, and aquifers. In highly gassy and soft coal seams, the low intensity of the coal-rock mass and the high gas pressure result in an increase in plastic zone radius and effective radial force. Drilling through layers of aquifer and weak walls leads to a decrease in the cohesion and frictional resistance of the coal rock mass, and thus, borehole deformation and collapse can happen easily. Deformation and collapse causes borehole blockage. With an increase in burial depth and extraction time, the probability of blockages occurring will increase [27].

The formative mechanism of blocked boreholes can be divided into three types as shown in Figure 2.

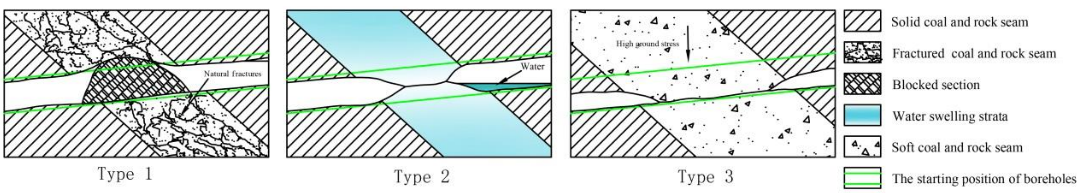

Figure 2. Schematic diagram of blocked boreholes.

In Type 1, coal-rock mass around the boreholes develops massive natural fractures, which causes crushing of the borehole wall. Under the combined action of gravity and gas stress, the collapsed coal drops and accumulates in the borehole to block the gas-flow channel. Type 2 occurs in water-swellable strata such as mud rock and marl seam. In these strata, borehole walls expand into the borehole after water swelling, and decrease the gas flow area and even block holes. Type 3 involves the direct closure of boreholes in soft coal and rock seam because of the action of high ground stress.

3. Method for Removing CBM Drainage Hole Blockage

The proposed blockage removal method of CBM drainage boreholes requires only simple equipment, but is practical and easy to install. A device connection schematic of the method is shown in Figure 3.

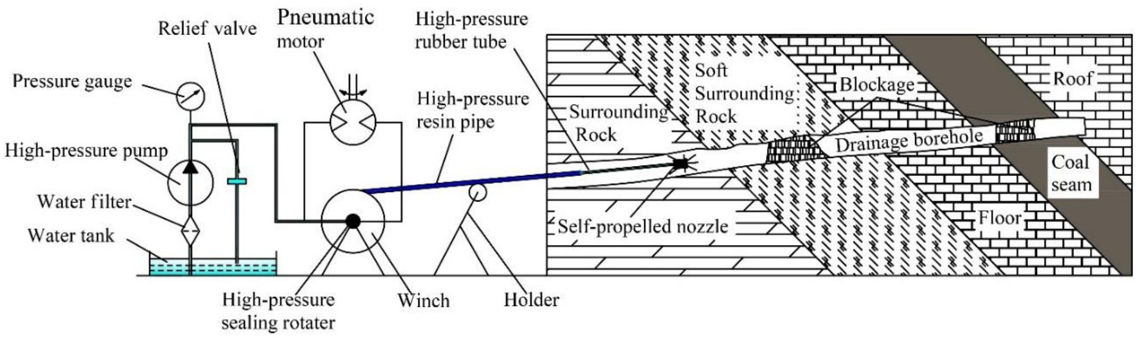

Figure 3. Device connection schematic of blockage removal method.

The detailed blockage removal process is described below.

Firstly, we decide whether a borehole is blocked or not according to the change in CBM drainage efficiency. (If the hole is the CBM drainage volume and the drainage concentration decreases suddenly when a nearby gas hole extraction efficiency changes slightly, we can assume that the borehole is blocked). Secondly, place a device in front of the blocked holes, and adjust a steering holder to contain a high-pressure rubber tube with a self-propelled water jet nozzle and the target borehole in alignment. (It is difficult for conventional cleaning machinery to match the original borehole direction because of the high drill pipe hardness. In the new method proposed in this paper, soft high-pressure resin pipe replaces traditional high-hardness pipe). The equipment is then opened to dredge and clean the boreholes. As the self-propelled water jet nozzle in the pitch pipe drives it ahead, the pneumatic motor keeps pushing the pitch forward at the rear and provides thrust in a certain axial direction so that the self-propelled water jet nozzle can drill in a wide borehole range. (The pitch pipe has a certain flexibility that takes advantage of the water flow recoil to keep the pipe in the middle of the hole and maintain the drilling direction during the cleaning process. Figure 4 shows the connection mode of the high-pressure resin pipe, high-pressure rubber tube, and hydraulic self-propelled nozzle). Finally, by reversing the air motor, the high-pressure resin pipe is wound onto the winding machine.

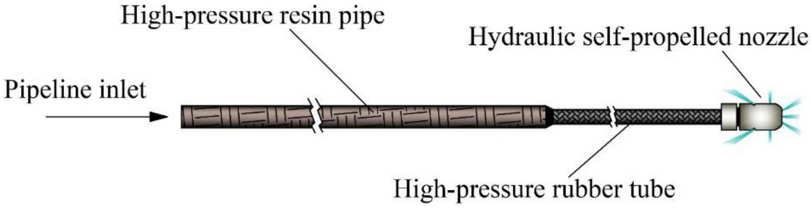

Figure 4. Device connection schematic for high-pressure resin pipe, high-pressure rubber tube, and hydraulic self-propelled nozzle.

The key to blockage removal from CBM drainage boreholes as proposed in this paper lies in high-speed water jet ejection from hydraulic self-propelled nozzles. High-pressure water jets with a high speed can crush blockages in collapsed sections and expel coal and rock debris from the borehole. As part of the drilling, hydraulic self-propelled nozzles form multiple orifices that point centrally forwards, backwards, and sideways (Figure 5).

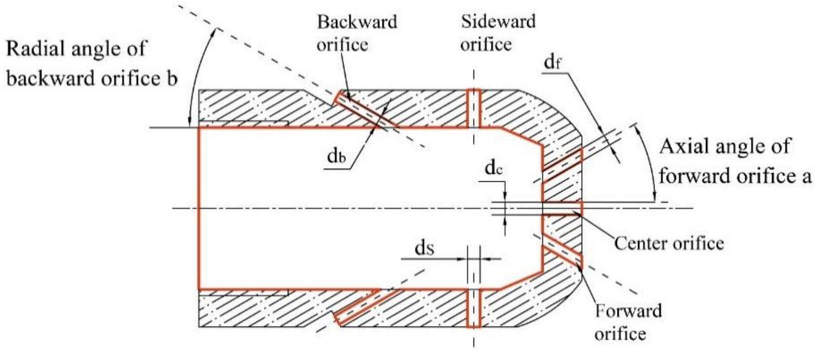

Figure 5. Structural diagram of self-propelled nozzle.

The central forward-pointing orifice directs high-pressure water jets (center jets) to break the rock (coal) to form relatively deep boreholes under the combined action of collision, stress waves, water wedging, and cavitation [28–30]. The forward orifices are arranged with an axial angle that can eject water jets (forward jets) with a relative high tangential velocity and shearing stress. During drilling, divergent jets expand the borehole to provide passage for self-propelled nozzles and the high-pressure rubber tube.

The sideward orifices eject water jets (vertical jets) perpendicular to the hole wall, which guarantees the distance between the nozzle and borehole wall and the right direction.

The backward-pointing orifice ejects backward jets, which balances the reverse thrust produced by the forward and center jets, and provides a drill thrust to pull the high-pressure rubber tube forward. The direction of the backward jets forms an angle b with the axial direction of the self-propelled nozzle. Because of the angle, the high-speed jet sprays the borehole wall and excludes drilling cuttings simultaneously. The self-propelling force of the self-propelled nozzle is [31]

$$F_Z = 1.57mpd_b{}^2\cos b - 1.57npd_f{}^2\cos a - 1.57pd_c{}^2 \quad (2)$$

where F_Z is the self-propelling force of the self-propelled nozzle in N, m is the number of backward orifices, d_b is the backward orifice diameter, b is the included angle between the reverse jet and the central axis of the drill bit, n is the number of forward orifices, d_f is the diameter of the side orifice, a is the angle between the side orifice and the central axis, d_c is the diameter of the side orifice, and p is the jet pressure. When m = 8, n = 3, $a = b = 25°$, $d_b = d_f = d_c$ = 0.6 mm, p = 20 MPa, and F_Z = 40 N.

The self-propelling force of the self-propelled nozzle is used mainly to pull the high-pressure rubber tube forward, and the mass of the rubber hose is approximately 0.1 kg. Therefore, the self-propelling force of the self-propelled nozzle is sufficient.

4. Experimental Study and Parameter Optimization

A field experiment was carried out in Songzao coal mine, Qijiang, Chongqing, China, to verify the feasibility of the blockage removal method of blocked CBM drainage boreholes. Before the field trial, we selected an appropriate nozzle inlet pressure by drilling a sample in the field (coal sample), and selected an applicable pitch pipe through a pressure loss test in the laboratory.

4.1. Optimization of Nozzle Inlet Pressure

When a high-pressure water jet is exerted in coal and rock crushing of different broken objects, the threshold pressure of the coal-rock mass for breakage and crushing differs. When the water pressure is too low, the high-pressure water jet cannot crush coal and rock; on the contrary, if the water pressure is too high, energy is wasted. The aim of the optimization of nozzle inlet pressure is to find a suitable pressure value meet the minimum pressure requirement of the site. Coal samples used in laboratory experiments were from the Fengchun Colliery where a field trial will be conducted. Entire samples were used with a firmness coefficient of 0.35, and coal sample crumbling was prevented using cement before the drilling experiment. The drilling experiment focused on the drilling efficiency of the hydraulic self-propelled nozzle under different nozzle inlet pressures. The free drilling speed can be represented as:

$$v = f\,(P, L, Q)\,. \tag{1}$$

where v is the drilling speed, P is the entry pressure (MPa), L is nozzle flow (L/min), Q is the physical properties of coal and rock. Because the diameter of the nozzle is a fixed value, so L has a correlation with P. That is to say, when P is constant, L is a constant value.

The results show that the threshold pressure of coal is 14 MPa; when the inlet pressure was 18 MPa, the drilling speed of the hydraulic self-propelled nozzle reached ~0.3–0.7 m/min and the borehole diameter was 35 mm, which meets basic requirements to dredge the boreholes.

4.2. High-Pressure Resin Pipe Selection

The selection of a pitch pipe length is determined by the CBM drainage borehole depth and the diameter is determined by the orifice diameter of the self-feeding nozzle. A test was conducted to determine whether requirements for blockage removal field experiment were achieved by testing the pressure loss in a resin pipe. The length of the underground CBM drainage boreholes in the Chinese coal mine were mostly between ~30 and 80 m. Combined with the borehole diameter of the laboratory experiment, the size of the resin pipe was selected with a length $\times$ diameter $\times$ inside diameter of 80 m $\times$ 17.2 mm $\times$ 12.7 mm. By testing the pressure loss of a resin tube in the laboratory, we found that when the pump pressure was 30 MPa, the flow rate was 58 L/min, and the pressure loss of the resin pipe was 10 MPa. When water reaches the nozzle, the pressure can be maintained above 18 MPa. Most coal mines in China use model BZW200/31.5 pumps (Liuhe Coal Mining Machinery Co., Ltd., Nanjing, China) with a maximum rated capacity of 200 L/min at their maximum rated pressure of 31.5 MPa, so this resin tube is appropriate.

5. Field Experiment

5.1. Field Experiment Site and Geological Conditions

A field experiment was conducted at a 3–2 drill site of the main railway in level of 460, Fengchun coal mine, Chongqing, southwest China. Figure 6 shows a sketch map of the experimental site.

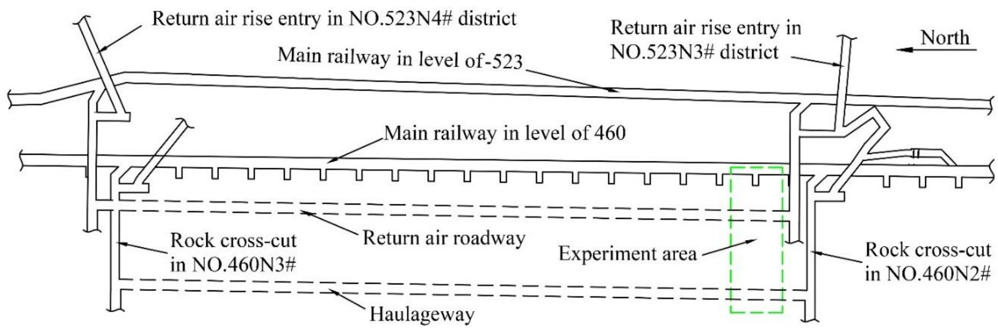

Figure 6. Sketch map of experimental area.

The depth of the experimental area was ~339.4–428.5 m, and the ground elevation was +801.9 to +889.4 m. The lithology of this region is mainly sandy mudstone, sandstone, marl mudstone, and coal seam. The roof and floor of the coal seam normally present a relatively unstable sandy mudstone and mudstone. Figure 7 shows the lithology of the strata in the experimental area. The coal petrologic horizon is normal. Specific coal seam properties are presented in Table 1.

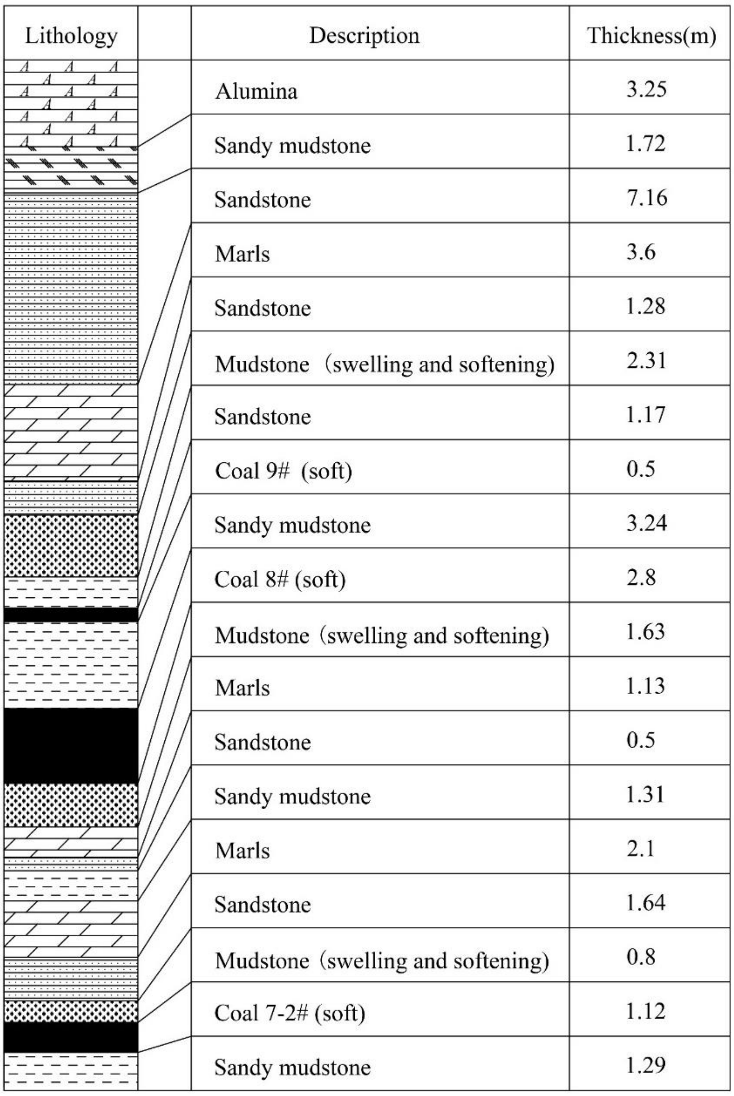

Figure 7. Lithology of strata in the test area.

Table 1. Properties of the coal seam.

Properties	Value
Mean tilt angle	55°
Average propensity	292°
Thickness of M2-7 coal seam	0.91 m
Thickness of M8 coal seam	2.29 m
Thickness of M9coal seam	0.4 m
Methane content	18.09–25.87 m^3/t

According to the colliery's geological repot, the Fengchun coal mine is a typical gassy soft coal seam, and often contains blocked CBM drainage boreholes. In some areas, blockages reach as high as 83.5%. During CBM extraction in the Fengchun coal mine, if the CBM drainage concentration suddenly decreases to below 5% or the CBM drainage volume suddenly decreases below 1 m^3/day ("m^3/day" means the CBM drainage volume per day) while the nearby borehole drainage situation changes little, we can tell that the hole has been blocked. Using anchor drill tools to dredge blocked boreholes artificially is common in Fengchun coal mine but has a very low success rate. Without timely dredging, these boreholes are eventually abandoned.

5.2. Testing Equipment

The main equipment used in the field experiment is the hydraulic self-propelled blockage removal equipment. The equipment comprises a controller cabinet, winch, propulsion mechanism, water pipeline, and air pipeline. The controller cabinet mainly controls the air intake of the pneumatic motor and the flow pressure. The winch is used to wind the resin pipe. The propulsion mechanism uses the pneumatic motor to provide thrust and pull, and the resin pipe can be moved forwards and backward. The water pipeline includes mainly an 80-m resin pipe and a 0.6-m rubber tube. The front end of the rubber tube is equipped with a hydraulic self-propelled nozzle as shown in Figure 8. A high-pressure pump, model BZW200/31.5 (Liuhe Coal Mining Machinery Co., Ltd., Nanjing, China) was used [32,33].

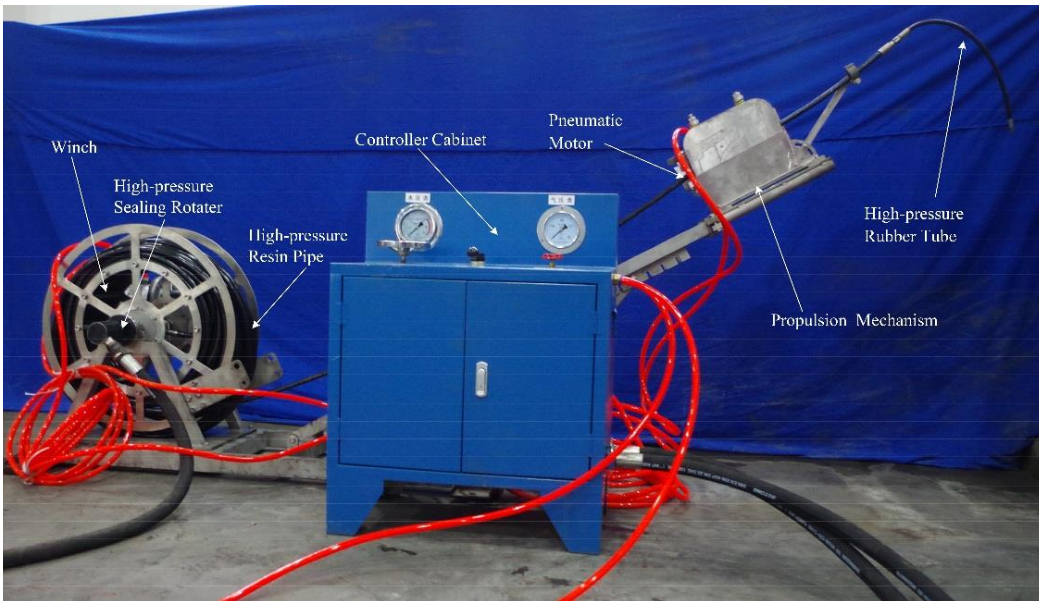

Figure 8. Blockage-removing equipment with hydraulic self-propelled nozzle.

5.3. Experimental Design and Drilling Parameters

The coal seam protodyakonov coefficient at the test site was ~0.2–0.3, the coal seam was soft, and the plugging rate of the CBM drainage boreholes was very high at the 3-2 drill site. We chose 12 random blocked boreholes from the 3-2 drill site. Each blocked borehole's diameter was 87 mm with a five-meter-long screen pipe under the borehole opening (The main function of the screen pipe is to prevent borehole collapse, but the screen pipe will reduce the coal wall exposure area and decrease the effect of CBM extraction. The screen pipe in the coal mining process is also difficult to extract and will reduce the coal mining efficiency. Each borehole is equipped with a screen pipe of only 5 m). Table 2 shows the structural parameters of the boreholes.

Table 2. Structural parameters of the drainage boreholes.

Number	Direction Angle/(°)	Elevation Angles/(°)	Length of Boreholes/(m)	Number	Direction Angle/(°)	Elevation Angles/(°)	Length of Boreholes/(m)
1	−72.2	82.5	66.3	7	38.2	45.4	51.2
2	0	70.2	52.2	8	−35	37.1	50.3
3	58.4	68.3	58.4	9	33.8	32.9	48.3
4	−44.3	61.2	52	10	−31.2	25.8	51.8
5	47.3	57.3	53.1	11	0	24.1	45.9
6	0	47.2	44.8	12	0	14.2	48.3

Because of the characteristics of water jet drilling, we avoided down and flat holes in the experiment (Self-propelled nozzles can be problematic in deslagging and dewatering during drilling. When this phenomenon occurs, the high-pressure resin pipe can get stuck easily).

Drill sites are arranged every 50 m along the railway, in a main railway at level 460, as shown in Figure 7. CBM drainage boreholes were drilled from each drill site to extract CBM of a certain range in front of the drill site. The 3-2 drill field arrangement is shown in Figure 9. After the CBM content is reduced to a safe level, a coal mining roadway is drilled along the coal seam from the rock cross-cut, and the coal face is arranged from the coal mining roadway. Finally, coal is mined from that region.

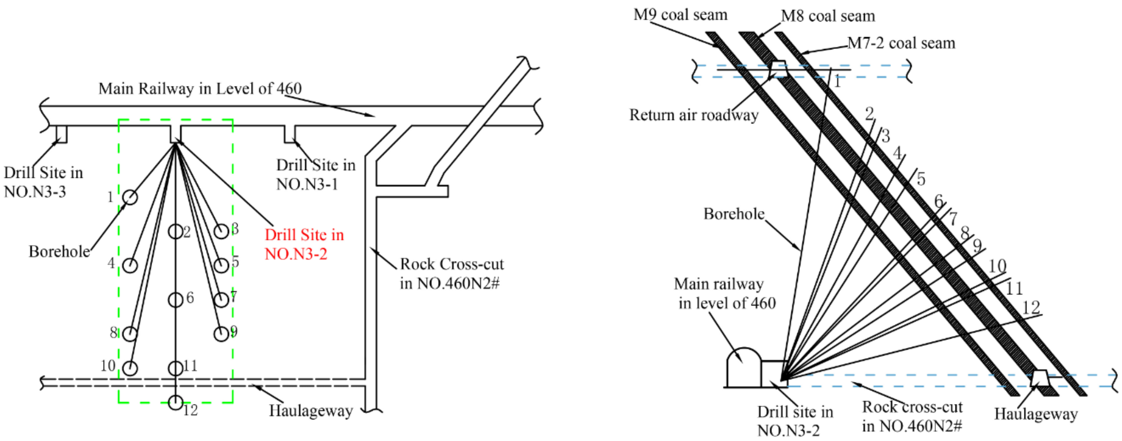

Figure 9. Arrangement of CBM drainage boreholes.

5.4. Analysis of Experimental Results

5.4.1. Analysis of Drilling and Blockage Location in the Borehole

The velocity of the self-propelled nozzle in the non-blocking section is greater than that in the blocked section. The nozzle reached the blockage, and the velocity of the high-pressure resin pipe dropped suddenly during the drilling process. After passing the blockage, the speed of the resin pipe increased rapidly. We therefore assume that the number of the blocked section is n (natural number), and i is the ith blocked section ($0 \leq i \leq n$). We assume that the length of the resin tube in the boreholes is equal to the dredging depth of the blocked boreholes.

During the experiment, we recorded the borehole length of l_0 and the time t_0 when we started dredging the blocked borehole. The drilling distance l_{ai} and time t_{ai} were obtained when the velocity of the high-pressure resin pipe decreased suddenly. Similarly, we recorded the drilling distance l_{bi} and time t_{bi} when the velocity increased suddenly, and recorded the drilling distance l_{max} and time t_c when the drilling distance reached the borehole design length or it became difficult to drill further. We also recorded the time t_e required to return the resin pipe.

After the experiment, we calculated the blockage length according to $= \sum_{i=1}^{n} (l_{bi} - l_{ai})$, the blockage removal time was $t_d = \sum_{i=1}^{n} (t_{bi} - t_{ai})$, the drilling speed in the blocked section was $v = l/t_d$, the dredging depth of the blocked boreholes was $l_q = l_{max} - l_0$, and the total time was $t = t_e - t_0$ (dredge one borehole).

According to experimental data and the boreholes structural parameters, we can construct a profile map of the blocked drainage boreholes as shown in Figure 10.

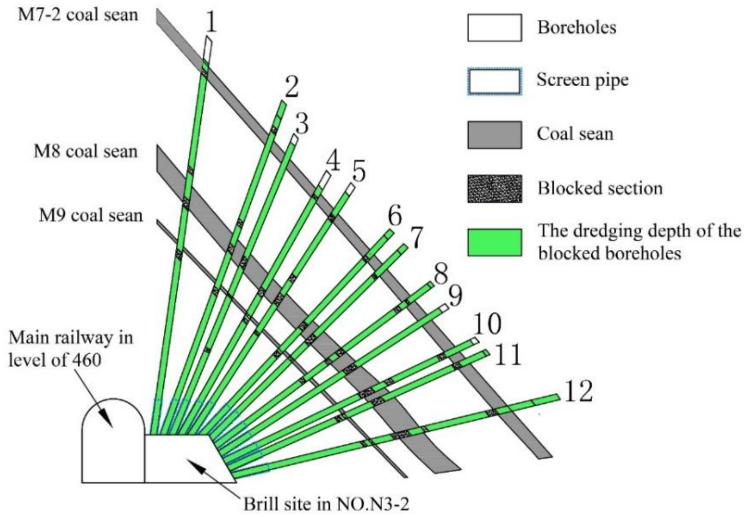

Figure 10. Profile map of drainage boreholes.

As shown in Figure 10, most borehole blockage occurs in a soft coal seam layer and mudstone stratum, such as the thicker M8 coal seam. The maximum forward length of the hydraulic self-propelled nozzle can approach or briefly exceed the initial borehole depth, which means that the new blockage removal method has relieved the blockage in the CBM drainage boreholes in this field experiment.

The field experiment also shows that the optimization of nozzle inlet pressure and selection of a high-pressure resin pipe meet the technical requirements for real construction to action. The pump pressure was maintained at ~28–30 MPa. The hydraulic self-propelled nozzle drilling speed in the blockage reached ~0.38–0.85 m/min, and the average speed was 0.62 m/min. The drilling speed in the blockage in this field experiment agreed with the laboratory results.

Because of a high probability of the CBM drainage boreholes being blocked in soft coal and rock seams, the blockage removal device used to dredge blocked boreholes must have a high removal efficiency and should be easy to operate. In this field trial, the time spent on one blocked borehole varied between 18.52 and 34.98 min, which is much shorter than that required to dredge one hole using a drilling rig (in this field experiment, it took an 8-h day shift to dredge all 12 blocked boreholes), and all 12 blocked boreholes were dredged. According to an analysis of the results, the blockage removal of CBM drainage boreholes proposed in this paper has advantages of a high work efficiency and good stability over any conventional blockage removal method of CBM drainage boreholes.

5.4.2. CBM Drainage Effect

After dredging the blocked boreholes, we extracted the methane immediately under a negative borehole pressure of 10 kPa and recorded the methane drainage concentration and the pure volume of the methane drainage of each borehole every couple of days. The extraction time was 1 month, and the results are shown in Table 3.

Table 3 shows that before blockage removal, the amount and concentration of methane drainage of each borehole was very low. The CBM drainage boreholes had lost efficacy. Blockage problems in the CBM drainage boreholes in the Fengchun coal mine lead to a decrease in CBM production and provided major insecurity in coal mine production.

Table 3. CBM drainage statistics for each borehole.

Number	Before Blockage Removal		After Blockage Removal	
	The Average Pure Volume of the Methane Drainage of a Single Borehole/(L/min)	The Methane Drainage Concentration of a Single Borehole/(%)	The Average Pure Volume of the Methane Drainage of a Single Borehole/(L/min)	The Methane Drainage Concentration of a Single Borehole/(%)
1	≈0.03	<5%	3.67	62
2	≈0.03	<5%	3.07	56
3	≈0.03	<5%	2.47	49
4	≈0.03	<5%	1.91	43
5	≈0.03	<5%	2.86	54
6	≈0.03	<5%	4.79	70
7	≈0.03	<5%	4.79	66
8	≈0.03	<5%	4.13	64
9	≈0.03	<5%	6.08	77
10	≈0.03	<5%	7.30	85
11	≈0.03	<5%	6.56	81
12	≈0.03	<5%	5.46	73

After blockage removal, the average pure volume of the methane drainage of a single borehole increased to ~1.91–7.30 L/min, and the methane drainage concentration of a single borehole increased to ~44%–85%, CBM drainage boreholes can return to service after blockage removal. The pure volume of the methane drainage of a single borehole is improved significantly over the previous volume. It has been proven that a decrease in the amount of CBM drainage and the methane drainage concentration resulted from the borehole blockage, which leads to difficulties in CBM extraction from the coal seam. The hydraulic self-propelled nozzle proposed in this paper can be used to dredge blocked boreholes to reopen CBM gas-flow channels, and this will definitely increase the CBM drainage efficiency.

We totaled the pure volume and amount of methane drainage in experiments on the 12 drainage holes, and calculated the methane drainage concentration. The results are shown in Figure 11.

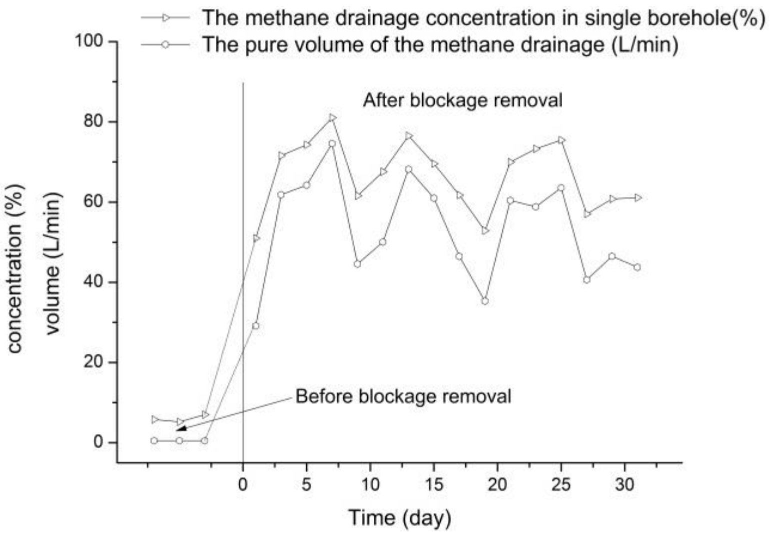

Figure 11. CBM drainage statistics of 12 boreholes over 1 month.

The normal use of blocked CBM drainage boreholes after dredging requires an improvement in extraction capacity after blockage removal, and the maintenance of a certain extraction capacity after a period of time. As shown in Figure 11, 1 month after blockage removal, the extraction ability of the boreholes was maintained at a relatively high level. Thus, the suitability and applicability of the blockage removal method of the CBM drainage boreholes was validated.

6. Conclusions

By analyzing the causes and types of blocked CBM drainage boreholes, a new method for blockage removal from CBM drainage boreholes was proposed. Blockages occur for two reasons: borehole instability damage caused by excavation and highly gassy Chinese coal seams usually have poor physical properties. This gives rise to deformation and collapse, and results in a blockage of shapes. This new proposed method aims to break blockages and drill new CBM passageways using hydraulic self-propelled nozzles. This increases CBM production and meets demands for its safe production in underground coal mines.

From laboratory drilling experiments, we learnt that when the entrance pressure of the self-propelled nozzle reached 18 MPa, the drilling speed reached ~0.3–0.7 m/min and the borehole diameter was 35 mm, which meet requirements to dredge boreholes. In addition, a high-pressure resin pipe was selected according to Chinese coal mine conditions, which eliminates the difficulties in matching the original borehole direction using a power drill and it is superior to the technologies used and developed for the same purpose.

Field experiment testing of this method in the Fengchun coal mine showed that blockage removal of the CBM drainage boreholes could be used to dredge blocked boreholes, and increase CBM production. The time spent on one blocked borehole varied between ~18.52 and 34.98 min, which was much shorter than the required time to dredge one borehole conventionally. After dredging the blocked boreholes, the methane drainage concentration of a single borehole increased from 5% or less to ~45.6%–82.7%, and the pure volume of the methane drainage of a single borehole increased from 1 m^3/day to ~6.9–11.7 m^3/day in each borehole. This improves the extraction ability of blocked boreholes significantly.

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