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Paper

APPLICATIONS OF SELF-EXCITED PULSED WATER JET IN UNCOVERING ROCK CROSS-CUT COAL OF CHINESE COAL MINES

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ABSTRACT

The safety situation of coal mining in China, especially the southwest is serious for the complex methane and geological conditions. The permeability of coal seam in these areas is as low as 9.37e-5～1.73 e-3 m^3/(MPa2.d), the methane pressure is as high as 2.5～6.0 MPa, and the period of rock cross-cut coal uncovering is more than 6 months. To solve those problems, a new idea of drilling and slotting in coal seam with self-excited pulsed water jet is proposed to improve the permeability of seam, increase the methane desorption rate, and shorten the cycle of rock cross-cut coal uncovering. For this purpose, characteristics of self-excited pulsed water jets and effects on cracking coal seam are investigated, and the devices for drilling and slotting with self-excited pulsed water jet are designed. The hydraulic parameters of self-excited pulsed water jet and nozzle structure are optimized by analysing the relationships between the pump pressure, flow rate, the depth and width of cutting, and the methane adsorption rate. Practical applications in Feng-Chun coal mine, Songzao Coal-Electricity Co. Ltd. Chongqing, China show that this technology can produce over 1.5m deep slots in coal seam, and the methane can be desorbed more freely. Investigation indicated that and the amount of gas drainage of cut hole increases by 4.4 times over uncut hole. The quantity of holes and the construction period decrease by 60% and 70 days respectively.

1. INTRODUCTION

It is a work of high risk and technical difficulty for rock cross-cut coal uncovering. It sometimes becomes a bottleneck problem of the reasonable deployment of coal. According to the statistic, coal and gas outburst is most serious in Chongqing of China. The largest outburst scales of coal happened in the rock cross-cut coal uncovering face. Oversize gas outburst happened 8 times in Nan-Tong Mining bureau in which it happened six times in the face of rock cross-cut coal uncovering. It is about the 75% of the oversize coal and gas outburst. The largest outburst scales is 8750t/time, and the gas emission is 1400,000 m^3. The risk of rock cross-cut coal uncovering is larger than that of heading face and coal face. It has some characters such as large outburst scales and scope, which brought great threat to the safety of miners and great losses of the national property.

Over the years, Chongqing had developed many technical measures to rock cross-cut coal uncovering such as hydraulic flushing, emission drilling, gas predrainage, asymptotic method outburst protection technology, metal skeleton and so on. These technologies are used on geological conditions of different coalfield, seams and outburst risks. Though these technologies have brought about a certain effect in the outburst prevention, these measures have complex crafts, and uncovering coal period is too long (usually more than six months), which has seriously affected coal production safety and normal relay. Thus, on the basis of safety production in coal mine, it is necessary to find a new technology of rock cross-cut coal uncovering to shorten the time of coal uncovering and ease the tense situation of work face relaying [1]- [4].

In this paper, self-excited pulsed water jet slotting and its' stress and dynamic effects of coal breaking will be studied. The relationships between the hydraulic pressure, slitting depth and width and soft coal seam fracture are investigated through laboratory tests. And the hydraulic parameters are optimized. Finally, it was applied in Feng-Chun coal mine of Songzao Coal-Electricity Co. Ltd. Chongqing.

2. APPLICATION PRINCIPLE OF SELF-EXCITED OSCILLATION PULSED WATER JET

Basing on the unstable characteristics of the water jet, continuous jet could turn to the fluctuation and the impact water jet, named self-excited oscillation pulsed water jet ,which is produced by closed-loop feedback and amplification of vortex rings fluctuation of water jet， gained from adjusting parameters of the fluid and the vortex structural of the continuous water jet.The shocking force of the target is a kind of high-frequency impact load.Tests and field applications prove that this impact load produced by self-excited oscillation pulsed water jet is 1.5~2.5 times bigger then that produced by continuous jet, greatly enhancing the damaging effects of erosion on the target material.

2.1 Principle of self-excited oscillation pulsed water jet

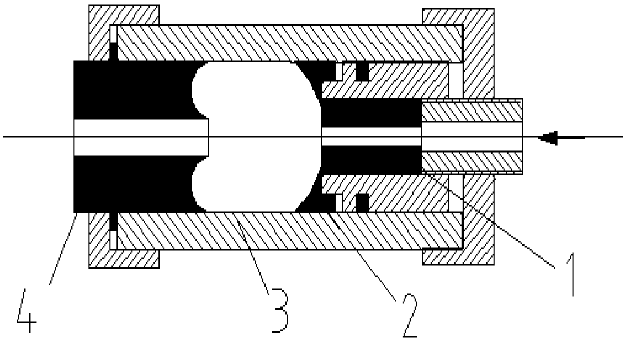

Figure 1. Self-excited oscillation nozzle structure

1 .Upperstream nozzle 2 .Upperstream impinge wall 3 .Oscillation chamber 4 .Downstream nozzle

Self-excited oscillation nozzle is mainly composed of four parts: 1.upperstream, nozzle, 2.upperstream impinge wall, 3.oscillation chamber, 4.downstream nozzle.
Working principle of the nozzle producing self-excited oscillation pulsed water jet is similar to the role of a Helmhotz oscillation. The high-speed water jet beam ejects from the front nozzle, under the function of the oscillating cavity, produce a disturbance on the jet surface and form a series of vortex rings. After the collision between vortex and the nozzle wall, it generates pressure pulse which forces the fluid in front of the vortex to accelerate, and on the other hand make the fluidity behind the vortex slow down.

When pressure shock wave in the opposite direction transmits to the front nozzle with a hypersonic jet speed, it collides with the nozzle wall and forms the pressure pulse again. With a nozzle exports wall collided, the pressure pulse brings about the oscillation of fluid in the nozzle and induces new vortexes on the one hand, then it floats to the backside along the jet. If the reflected wave coincides with the arrival of a scroll and then collides with the nozzle wall, the pressure pulse under collisions will be strengthened. If this process cycles, it will result in substantial jet pressure and pulse rate, and develops a strong pulse jet of water, thereby reducing energy consumption, raising the jet erosion effects.

Figure 2 described in a submerged state, where the system pressures are $P_0 = 2MPa$, $\frac{d_2}{d_1} = 1.4$, $\frac{D}{d_1} = 8$, is the jet wave of pressure when the lower collision wall is concave-shaped .

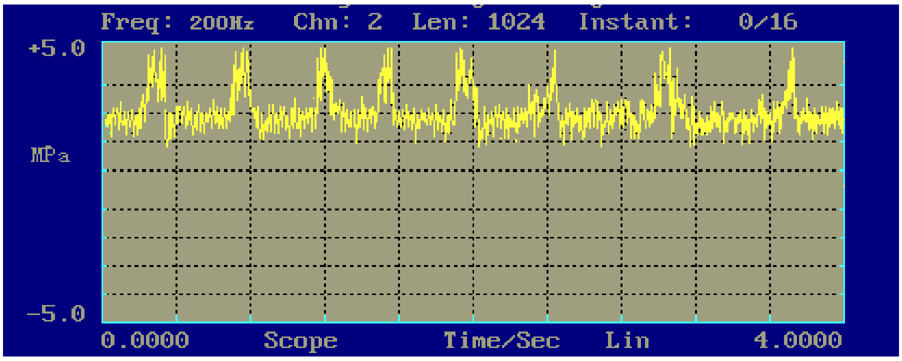

Figure 2. Jet wave of pressure

It can be visibly seen from Figure 2 that under the flooded conditions the flow of the largest instantaneous pressure of self-excited oscillation pulsed water jet is about 2.5 times of pump pressure, and the effective target distance is above two times than that of the ordinary jet.

2.2 Slotting principle of self-excited oscillation pulsed water jet

During the self-excited oscillation pulsed water jet slotting the seam, due to self-oscillation pulse water jet impact, vibration, quasi-static pressure and physical effect, on the one hand causes the change of coal and rock skeleton stress, leading to the change of coal properties (Such as modulus of elasticity, strength and penetration, etc.), thus affects the gas flow in the cutting of coal seam and distribution of pressure. On the other hand the state of gas migration changes lead to coal skeleton stress changes.

Stress waves (as shown in Figure 3) are produced by impacting in self-excited oscillation pulsed water jet. The areas affected by a powerful stress wave are in a state of absolute pressure. When the shock waves produced by the jet impacting coal spread to the coal-free surface, the stresses suffered by the coal change from the compression stress on the incidence into a pull stress when totally reflected. When the pull stress exceeds the tensile strength of part of the low-intensity coal, coal will break down on the stretch and form the cracks.

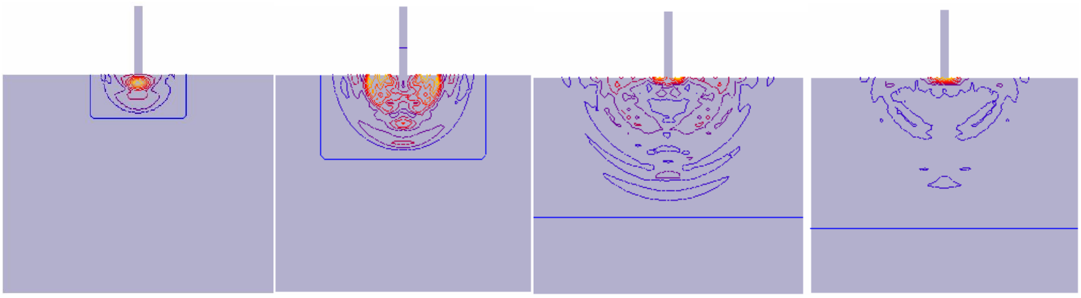

Figure 3. The spread Map of stress wave in the coal seam

This stress wave has two effects on the gas seepage: first, it leads to a complete change of the original stress distribution from the coal and stress-induced changes in coal fracture. When the gas analyzes, the surface tension of coal particles will increase and the coal will be contracted, resulting in its smaller size and the enlarged fissures, as well as the pore size. On the other hand, the changes of fracture rate will cause the changes of gas permeability coefficient. Impact of the stress wave spreads in the form of seismic wave, bringing about the shock effect from coal deformation, and leading to the disturbance of the original gas balance such as temperature, pressure in the cracks and causing fluctuation of gas in the fissures. Volatility will rise up the temperature - that is, thermal effects which will aggravate the gas desorption. At the same time the volatility of gas will cause the partial vibration of the fracture. Fluctuations caused by vibration and thermal effects will change along with the degree of stress-wave change.

After the implemented slotting in coal seam, it not only increases the free surface of the gas overflow, but also develops a larger scope of the high permeability fracture zones around the cutting slit result from the breakdown of coal and consequently brings more substantial increase in the gas transport channels, enabling gas pumping with a larger gas-pumping speed at the early age of gas mining.

3. LABORATORY TESTING TO OPTIMIZE THE HYDRAULIC PARAMETERS

Coal samples were taken from uncovering rock cross-cut coal place. Through laboratory manufacturing, briquettes and small coal specimens are formed. Through laboratory testing, we studied the interrelationship between oscillation pulse water jet's pressure, flow, nozzle structure, the nozzle layout, etc and that of the cutting groove depth, width and permeability coefficient of soft coal seam, and optimized the hydraulic parameters of the pulse of the oscillation of water jet cutting coal seam.

3.1 Test principle

When the mechanical bits bore at the bottom of the hole drilling, then pump pressure is increased, self-excited oscillation pulsed water jet in the radial direction begin to cut the slot, while mechanical drill moves back, driving the oscillation nozzle installed on the drill movement which cuts a deep trough on the drainage hole in the radial direction. As a result, it increases the exposure of coal and improves fissure rate of the soft coal seam (as shown in Figure 4).

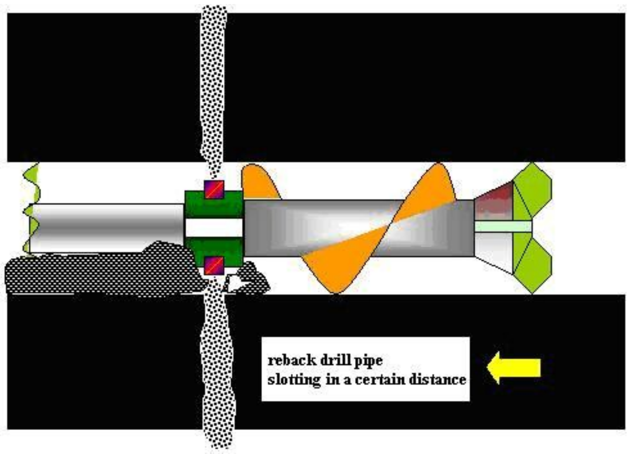

Figure 4. Oscillation pulse water jet slotting Principle

3.2 Laboratory tests

Laboratory cutting coal was from the Feng-Chun coal mine, Songzao Coal-Electricity Co. Ltd. Chongqing,China. We put the collected coal block into a wooden box and enwrapped it with cement in order to prevent its fragmentation. The solid coefficient of the coal is 0.35, and the nozzle speeds 10 mm / s. The effect of cutting in the experiment is studied by adjusting the target distance and pump pressure. The typical data of cutting is revealed in Figure 5 and 6 below.

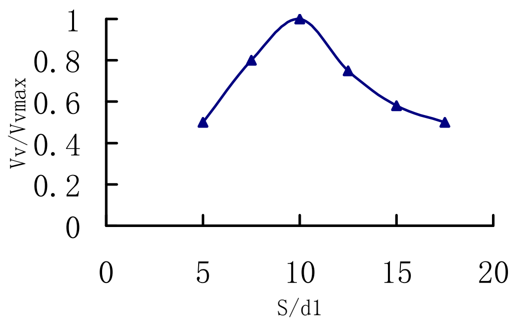

Figure 5. The relationship between the target rate and volume removal rate

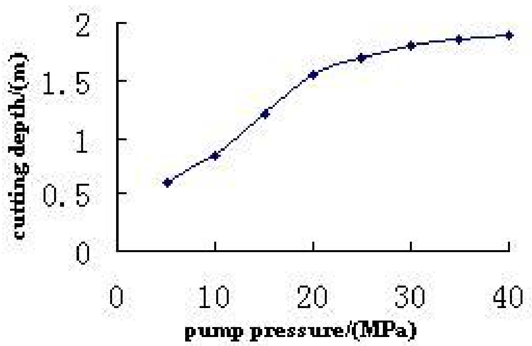

Figure 6. The relationship between the pump pressure and slotting depth

From figure 5(d1 is the nozzle diameter: Vv=V/t, is impact erosion volume rate, or volume removal at unit time), we may find that impact erosion volume rate increases accompanied by the increase of target distance, and it will reach the maximum when target distance reaches 10d1. Then with the increasing of target distance, the volume removal rate starts to reduce. Thus, 10d1 is the best target distance. Also, from the laboratory test results, as shown in Figure 6, when the water pressure advances to more than 20 MPa, the cutting depth will reach 1.5 m above, which ensure increasing the coal permeability.

4. APPLICATION STUDY IN FENG-CHUN COAL MINE

4.1 Tests in Feng-chun coal mine

4.1.1 Test equipments and connection

Figure 7. ZY-1250 fully hydraulic drill for coal mine

Layout map of experimental device is shown in Figure 8.

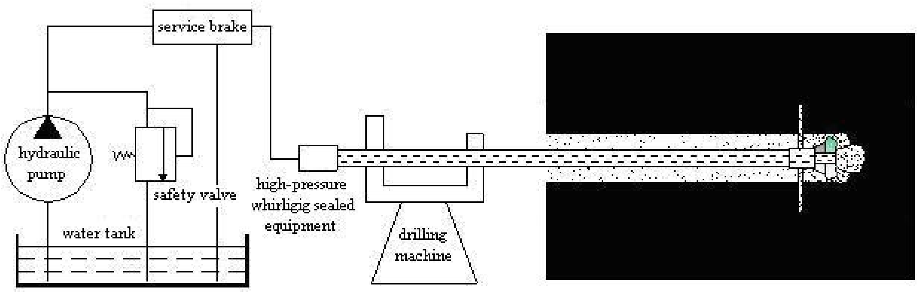

Figure 8. Sketch map of device connection

4.1.2 Geohydrology conditions of experimental sites

In Feng-chun coal mine, the experimental sites are chosen in the election of mine +523 S4-track roadway M8 coal floor weeping 2 m from the department. The average dip angle of the seam in this region is 50 °, the average inclination is 297 °. The thickness of M6-3 coal seam is 0.75 m, M8 seam thickness 1.61 m, M7-2 seam thickness 1.07 m. Ground elevation is 990 ~ 1052 m, M8, M7-2 coal seam open at depth 467 m. The spacing of M8 and M9 coal layers suffer a larger change. It will be badly impacted by the faults to analyze the M8 coal seam. Coal gas in this region: M8 seam 23.47 m^3 / t; M7-2 seam 18.31 m^3 / t; M9 seam 18.21 m^3 / t, with both coal and gas outburst risk. Experimental regional lithology proceeded from Maokou limestone to coal excavation. The mainly compositions of lithology are limestone, sandy shale and mudstone, sandstone, marl and coal. The coal seam roof and floor are largely composed of sandy shale and mudstone. The layer of coal rock is basically normal.

4.1.3 Drilling design for slotting and analysis of test results

According to the information of geohydrology and the relevant data of past rock cross –cut coal uncovering in Feng-chun coal mine, we design a field test scheme of nine drilling-hole designed in all. Sketch map of coal seam slotting is depicted in Figure 9.

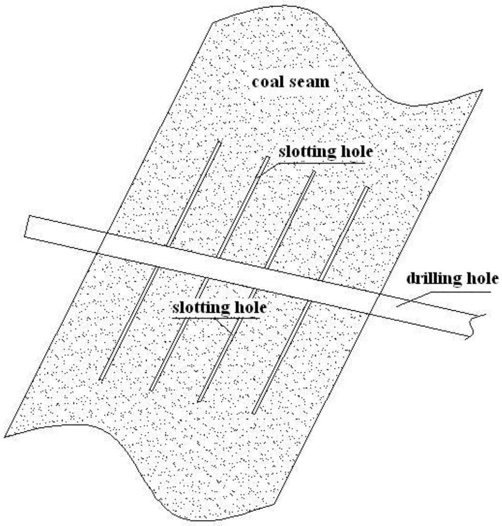

Figure 9. Sketch map of coal seam slotting

（1）Quality of gas emission in slotting

We recorded the data of the gas in the back wind when self-excited oscillation pulsed water jet slotting, and then calculated the volume of gas. In the end we compare it with the gas absorption without slotting. See detail in Figure 10, 11.

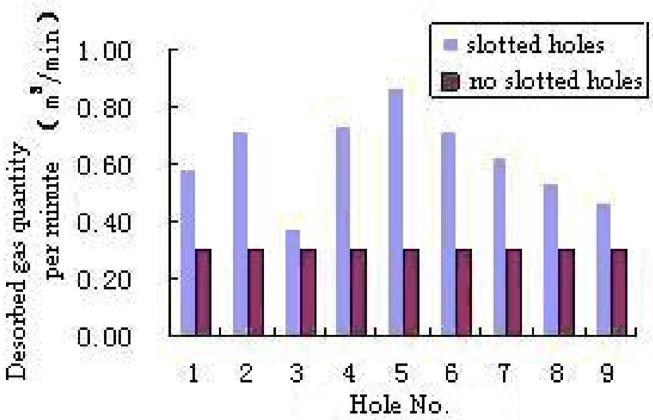

Figure 10. Comparison chart of the desorbed gas quantity per minute before and after slotted

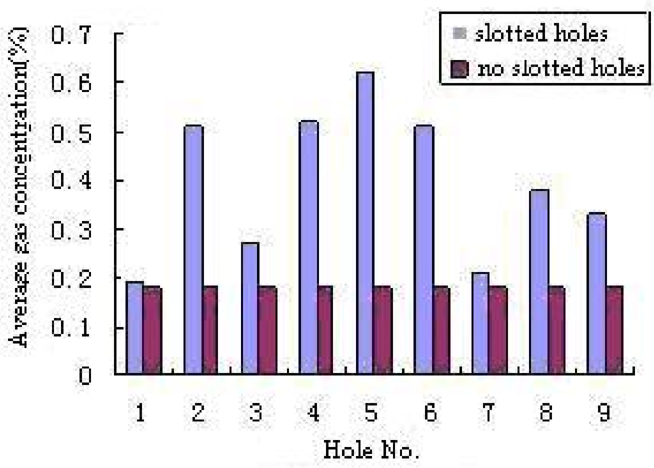

Figure 11. Comparison chart of average gas concentration in slotted-holes and test-holes

Seen from Figure 10, the coal seam is acted by self-excited oscillation pulsed water jet and the gas release channels increases, the exposed coal seam area enlarges, the gas desorption substantial increases in volume. It improves the gas by 293 percent comparison of natural emission without slotting. The average amount of instant pure gas is 0.6 m^3/min. Figure 11 can be seen, compared the gas desorption from slotted with that from no slotted, it is 220 percent increased. Obviously, effects of gas desorption improved greatly.

（2）Gas situation after slotting

After completion of slotting by self-excited oscillation pulsed water jet, Gas concentration in return air return 0.18 to 0.35 percent, gas emissions to 362.9 ~ 625 m^3, as are seen in Figure 12, 13.

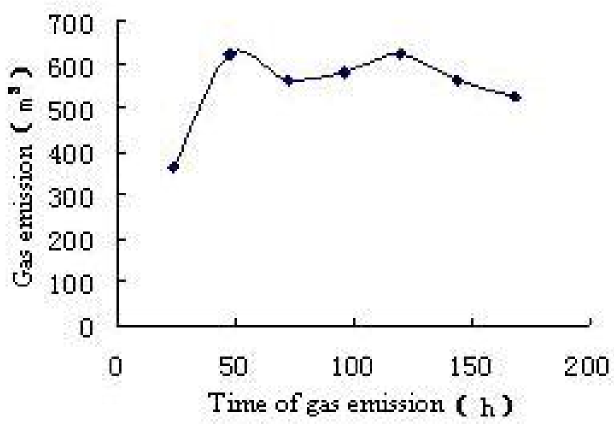

Figure 12. Curve of methane emissions quantity after slotting

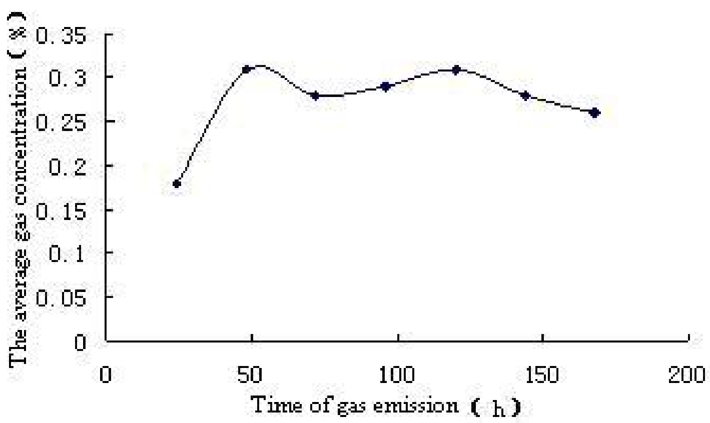

Figure 13. Changes of the average gas concentration after slotting

Figure 12, Figure 13 show that after completion of slotting by self-excited oscillation pulsed water jet, the average gas emissions reaches to 0.342 m^3/min, while that is only 0.128 m^3/min in the former of no slotting, it increases 170 percent. Adopting the natural emissions of gas after slotted have obviously effects.

（3）Detection of outburst dangerous

It has slotted by self-excited oscillation pulsed water jet two days later, we use the method of gas desorption index of drill-cuttings to check the effects of slotted. Five test drilling are constructed , among them, three bored have no resistance in drilling, Results show that they reach in affected areas by self-excited oscillation pulsed water jet. The other two bored measured K1max = 0.47, Smax = 4.3Kg, as are seen in Table 1.

Table 1. Test results

Number of hole	K1max	Smax（Kg）	phenomena
1		empty slot without cuttings reversing out	
2		empty slot without cuttings reversing out	
3	0.29	3.7	none
4	0.47	4.3	light squirt from the hole
5		empty slot without cuttings reversing out	

Table 1 show that the gas absorption and release critical value K1 and cuttings content Smax don't exceed the required standards. Furthermore it is proved that slotting by self-excited oscillation pulsed water jet has a good effect of elimination outburst. In addition, three drill pipes reach into slit that further show self-excited oscillation pulsed water jet has the function to increase the slit size.

（4）The affected areas of self-excited oscillation pulsed water jet

According to the parameters of test boreholes and slotting holes, the results of calculation of test drilling and slotting as are shown in table 2.

Table.2 Bottom space between proof-test holes and slotted holes

parameters of proof-test hole				parameters of slotted hole by jet				bottom space between slotted hole（m）	the least bottom space between slotted hole（m）
no. hole	direction angle（°）	elevation（°）	hole depth（m）	no. hole	direction angle（°）	elevation（°）	hole depth（m）		
1	13	-13	21	1#	10	-12	20	0.74	0.74
				5#	8	-7	19.6	3.08	
2	11	-9	19.7	6#	4	-4	22	4.06	1.5
				5#	8	-7	19.6	1.50	
3	1	-7	16.7	7#	-2	-9	23.1	6.21	6.21
				8#	-14	-6	25.8	10.54	
4	-2	-12	34.5	3#	-1	-12	24.6	9.01	7.97
				4#	-6	-12	24.7	7.97	
5	5	-13	21	2#	5	-12	21.5	0.56	0.56
				3#	-1	-12	24.6	4.31	

Seen from Table 2, we find that when the bottom spaces of test holes and slotted holes are less than 1.5 m, there are no drill cuttings backing from the proof-test holes. This illustrates that the radiuses of self-excited pulsed water jet slotting is 1.5m above, $2^{\#}$ test hole enters into slotted areas of $6^{\#}$ hole. When the distances of holes reach 7.97 m above, slight outburst appears in the testing hole. This illustrates that the testing hole is out of the scope of avoiding outburst by self-excited pulsed water jet slotted.

5. CONCLUSIONS

（1）Through the laboratory testing, the erosion volume of coal will reach the maximum when target distance reaches 10d1. When the pump pressure advances to more than 20 MPa, the cutting depth will reach 1.5 m above. This will ensure the requirement of improving the coal seam permeability.

（2）The technology of outburst prevention by using self-oscillation pulse water jet slotting is applied in rock cross-cut coal uncovering of high gas and low permeability coal seam in southwest coal mine China, which solves the problem that using traditional ways are more drilling holes, heavy workloads, big difficulty to construction, long construction time. But using the technology of self-oscillation pulse water jet slotting reduces greatly the amount of drilling holes, and shortens the construction period for over 70 days, enlarges the exposure area of outburst coal seam, increases the radius of drawing gas out, quickens the speed of gas drainage, improves the work efficiency, saves much cost and thus increases the economic benefits.

（3）With the continuous innovation of the self-oscillation pulse water jet technology, it has a very wide prospect to be applied in the field of pre-drainage and outburst prevention of coal mines. Though this test is successful, there are a lot of problems to solve when using it in different coal mines widely. For example, when there are problems of declination drills or long drilling slots backing drill cuttings, the big loss of hydraulic pressure energy by drilling and self-oscillation, large difficulty in the adjustment of the structure parameters of jet equipments due to the different hardness of the coal, and the high consumption of the equipment energy, etc. All these problems need further and deeper investigation and study.

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