Study on Comprehensive Treatment Measures of Low Permeability and Gas Outburst Coal Seam Base with Hydraulic Flushing

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Abstract
The coal seam condition of test coal mines is low permeability, large dip angle, soft coal,and low gas drainage rate. This text researches hydraulic flushing as pressure relief and increased permeability measures. It adopts theory analysis, numerical simulation, and field testing to research key technology for hydraulic flushing. It combines previous studies of "three-steps drainage method", propose to gas comprehensive treatment measures. First, it studies coal breaking mechanisms of high-pressure water jets and confirms the water pressure of hydraulic flushing. Next, it adopts numerical simulation and field testing to study the scope of influence. Finally, it studies the gas treatment effect of gas comprehensive measures after the measures have been carried out. Studies show that the result of influence scope between numerical simulation and field tests are close. The final influence scope confirms at 4.5m. Adopting the inspection of the weight of washed coal, residual gas pressure, residual gas content verified the effectiveness of measures. These measures achieve the aim that gas drainage rate increases, quantity measures are reduced, engineering time is reduced, and safety and quickly eliminate the outburst danger of working face, The study guarantees safety production of similar coal seam condition as the test coal mine.
Keywords: HYDRAULIC FLUSHING, GAS OUTBURST COAL SEAM, LOW PERMEABILITY, NUMERICAL SIMULATION, GAS DRAINAGE, FIELD TEST

0 Instructions

Most coal mines began to mine the deep coal seam in China, and as the coal seam depth increases, the mine stress increases, the permeability of the coal seam is poor, the migration distance of gas increases, which is conducive to gas sequestration[1]. Based on the good status of gas seal, high gas content and great stress and so on, the coal seams that have no prominent danger appeared the dynamic phenomenon[2]. Outburst risk of original outburst mine got bigger and bigger, the frequency of outburst increased, the intensity of outburst intensity increased, the proportion of occurring large gas outburst grew, the casualties that caused by gas outburst increased significantly[3].

The experimental coal mine belongs to coal and gas outburst mine, the coal seam is soft and has

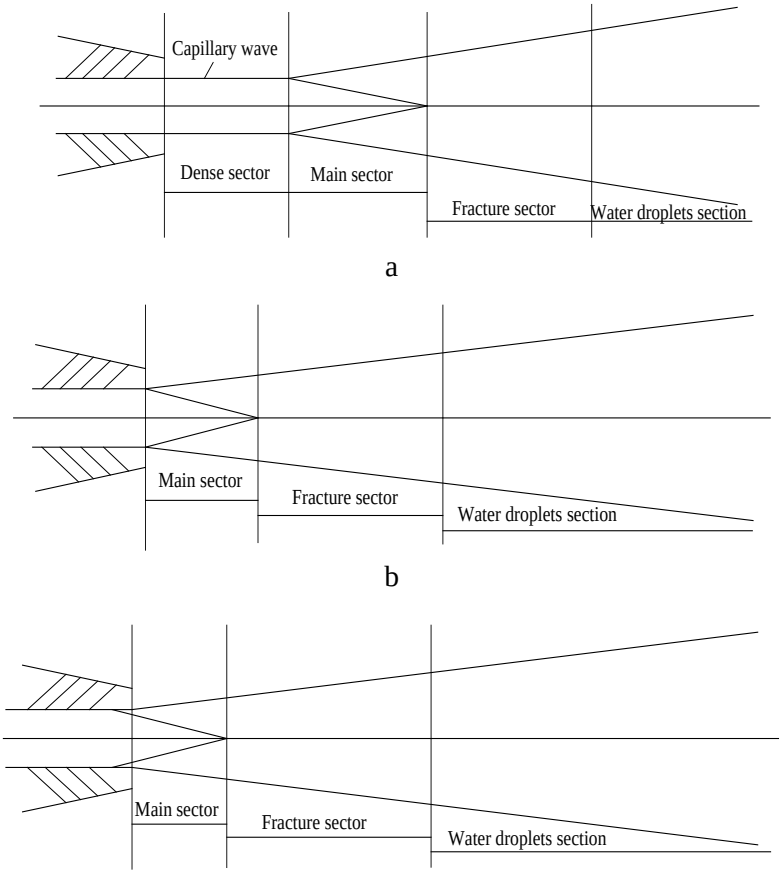
low permeability. The measures of controlling local gas cannot solve the gas overrunning of working face effectively[4-5], which include the drilling emission, pressure relief through drilling, shallow hole loose explosion and so on. The former Soviet Union had a comprehensive study on the hydraulic punching, and the measure of preventing outburst by opening the unloading groove along the roadway was proposed and the technology of opening the unloading groove is tested[6], which the effect is good. Based on the experiment of hydraulic flushing, Yu Qixiang[7] preliminary summarized the technology, equipment and system of hydraulic flushing, the method of test effect of hydraulic flushing. It is proved that hydraulic flushing is an effective measure to prevent gas outburst in theory and practice. The hydraulic flushing was successfully used in rock cross-cut coal uncovering and coal roadway tunneling successfully, but the technology of hydraulic flushing need to further improved, particularly in the aspect of separating coal, water and gas, and the method of test effect[8].

According to the actual situation of the experimental mine, the paper applied the technical measures of combining the pressure relief that used hydraulic flushing with the "three-steps drainage method" in solving the problem of controlling coal gas.

1 Mechanism of breaking coal by high pressure water pressure

Jet flow is a hole or slit out flow phenomenon. the water jet pressure of hydraulic flushing is in 10~18MPa, which belongs to high pressure water jet range, hydraulic punching water jet is mainly for cutting coal seam, the experimental area is floor roadway and the hydraulic flushing holes are all the upward drainage hole, so the hydraulic flushing water jet belongs to non-submerged water jet that is divided by the surrounding medium.

Non-submerged water jet is that the water medium than has a certain energy eject from the nozzle into the air, according to the different pressure, the Non-submerged water jet can be divided into low, medium, high and ultrahigh pressure, and the structures are shown in Figure 1, a is the low pressure, b is the medium high pressure, c is the ultrahigh pressure. According to the different flow pattern, the Non-submerged water jet was divided into dense sector, main sector, fracture sector, water droplets section.



a-Low pressure;b-Medium,high pressure;c-Ultrahigh pressure

Figure 1. Structural characteristics of non-submerged water jet

(1) Dense sector: the flow velocity of export section that is close to the water jet nozzle is close to the velocity of the water jet nozzle. With the distance that from water jet to the export section increases, the amplitude of water jet will increases, the water jet begins to breathe air when it increases to a certain extent, and its surface begins to rupture. Due to the less air that is inhaled, the surface of water jet ruptured and become large water masses.

(2) Main sector: The injection velocity of the core part still kept the initial state, and its state is compact. With the distance of water jet away from the nozzle increased, the basal area of core part slowly reduced and finally disappeared.

(3) Fracture sector: more and more air is inhaled in the water jet, the large water masses that generated on the surface of water jet were broken into droplets, the close state of the section jet center broken into the large water masses, with the distance of water jet away from the nozzle increased, the large water masses slowly reduced and finally become water droplets.

(4) Water droplets sector: the whole section of the water jet was isolated by air medium and become droplets.

For the high-pressure water jet, the high pressure lead to the results that the dense sector of water jet completely disappeared. There is a very large velocity difference on the boundary layer that formed by the water jet and object, and the force that is vertical to the axis direction of water jet, which is proportional to the velocity difference.

The diffusion law and the core length are the main geometric characteristic of the continuous water jet. The complex process lead to the imperfect study for non-submerged water jet, the main references are the laws and the empirical formula that are summarized by the experiment.

In figure 2, X_0 is defined as the length of initial segment, which include the main sector and the partial transition section. The length of main sector[10] is the position that the dynamic pressure of jet axis begins to attenuate, the initial attenuation law is related to the dynamic pressure of jet axis, and the late attenuation law is not related to the dynamic pressure of jet axis, which tend to be consistent.

According to a lot of experimental data, the former Soviet scholar plotted the relationship between the length X_0/d of the water jet initial segment's dimension that is 1 and the water jet pressure and the Reynolds number Re, and calculated the water jet initial segment's formula, which was shown in the following equations[9-11]:

$$X_0=(A-BR_e)d \quad (1)$$

$$R_e=\frac{Vd}{v}\times 10^{-3} \quad (2)$$

In the equation, X_0 is the length of the water jet starting section, mm; d is the exit diameter of nozzle, mm;

A is the empirical coefficient; B is the empirical coefficient, which is determined by Reynolds number; V is the velocity of water jet, m/s; v is the dynamic viscosity, m/s.

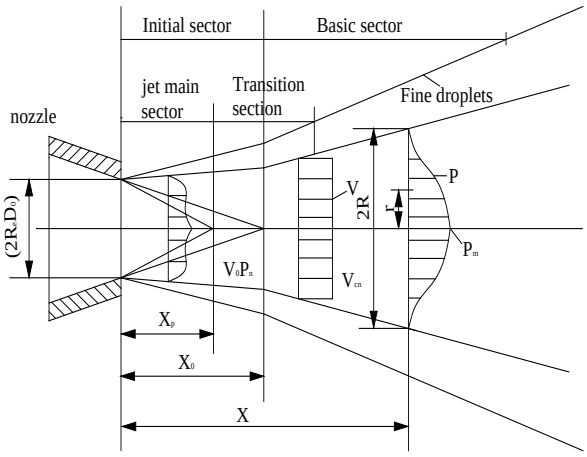


Figure 2. Structural representation of water-jet[10-11]

When the pressure of water jet is higher and the Reynolds number is that $Re>0.4\times10^6$, the X_0 can change in the following range:

$$X_0=(53\sim106)\,d \quad (3)$$

For the width of the water jet boundary, the following formula can be concluded:

$$\bar{D}=K\cdot\sqrt{X} \text{ or } b=k_1\sqrt{x} \quad (4)$$

In the equation, x is target distance, which the distance from section to exit section of nozzle; X is the target distance that dimension is 1, which is x/ d; d is the diameter of nozzle exit; D is the diameter of water jet spreading; $\bar{D}$ is the diameter of water jet spreading that the dimension is 1, which is D/ d; b is the radius of water jet spreading, which is D/ 2; K, k_1 is the coefficient that is related to nozzle structure.

The Reynolds number used in hydraulic flushing is related to the flow and inner diameter, which is generally larger than 0.2×10^4, and the core section length of water jet is related to the shape of nozzle and the quality of the nozzle.

In the basic sector, due to the exit of water jet is influenced by turbulent boundary layer, the initial

shapes of water jet that generated by different types are not identical, but the initial shapes of water jet have little influence on the turbulent boundary layer, the spreading of the water jet is relatively stable, because of going throught the initial segment,the jet flow in basic sector influenced by nozzle is also small,the water jet spread by the way of the following relations in the basic sector.

$$d = k\sqrt{x} \tag{5}$$

$$\frac{d}{R} = k_1\sqrt{\frac{x}{R}} \tag{6}$$

The distance(x) that the water jet is away from the nozzle exit can be concluded by simplified the formula (6),

$$x = \frac{d^2}{Rk_1^{\ 2}} \tag{7}$$

In the equation, *d* is the diameter of water jet; x is the distance that is away from the nozzle exit; R is the radius of the nozzle exit; k, k_1 is the coefficient that is related to nozzle, and the value of k_1 can be got from 0.12 to 0.18.

In order to ensure that the hydraulic flushing measures can play the full effect to relieve pressure and increase permeability, the coal output of hydraulic flushing are general 1% to 3% of coal weight that is within the control scope, the experimental mine the inclination direction of each drill field is 29m, alignment direction of each drill field is 36m, the density of coal is1.40t/m^3, the average thickness is 4.5m, coal quantity is 6577t through calculation in the control scope, and the output that is calculated by 1.5% is 98.65t, which means that the each hole is 4.9t, and the damage radius of coal is about 1m.According to the formula (3), the equivalent diameter of nozzle type that is suitable to the experiment mine is between 4.7mm and 9.43.

Hydraulic flushing measures generated a lot of coal body by high pressure water jet, which the coal body stress around the borehole redistributed when the protection layers of coal seam were exploited, large unloading zone appeared around the coal body of borehole, primary porosity and fracture went on expanding, rupturing and perforating so that a lot of gas kept generating and flew to the borehole through the tunnel, which increased the permeability of coal seam and improved the efficiency of extracting gas. It can be seen that the hydraulic flushing is the measure of relieving pressure and increasing permeability, which changes the permeability of coal seam by influencing the coal stress distribution around the drillings, and improved the permeability of coal seam.

2 Numerical simulation influence scope of hydraulic flushing

This text used COMSOL Multiphysics numerical simulation software to simulate the influence scope of hydraulic flushing.

The COMSOL Multiphysics numerical simulation software simulates and solves the different problems can be described by partial differential equations in scientific research. It is based on PDE modeling, it enables users to define and solve any multi-physics field coupling problem conveniently.It contains pretreatment,solver and aftertreatment,it provides great graphical user interface and rich modeling tool,it simplifys the complicated modeling work.The series of characteristic of COMSOL Multiphysics numerical simulation software is very suitable for the numerical modeling in engineering, scientific research and education.

In order to build the mathematical measurement model,the user need to build a partial differential equation which could accurately describe it and determine the definite condition.The accurate and reliable mathematical model of gas migration should be able to accurately reflect the actual gas flow field in coal mine.The flow of gas in coal seam affected by stress field, geothermal field, geoelectric field and other various factors, at the same time itself is in the extremely complicated geological conditions,the coal body has anisotropism,the condition of storage and transport of gas occurrenced in coal body is extremely complex.But from a macro point of view,in a larger area,besides the geological structural belts,the coal could be regarded as homogeneous.Thus, to simplify the problem, in the process of establishing mathematical model, set the assumptions as follows:

(1)The gas permeability of coal seam is much larger than roof-floor of coal seam,therefore, roof-floor of coal seam could be deal with as idealistic impermeable rock, gas is limited flows in coal seam;

(2)The permeability coefficent and gas pressure changes does not affect isotropic and porosity,but this increase exist in roadway and the released range around the borehole;

(3)The gas parameter is idealistic,the transfusion progress of gas could be deal with isothermal process;

(4)The absorbed gas conforms lundgren muir equation,the gas in coal seam desorbs in an instant;

(5)The flow of gas in coal seam obeys darcy law.

Before the numerical modeling with coupled equations,the structural mechanics module and gas flow field seepage module need to set boundary type and definite condition,then the coupled equations could get the unique solution. This type of differential equations have infinitely many solutions, on the basis of the results of the solution,this equation respectively gives the structural mechanics module and gas transport definite condition as follows:

The boundary type of the structural mechanics module:

(1) Displacement of fixed boundary.The bottom edges of coal and rock model is not changes.

(2) Free boundary. The upper boundary of model is set as free boundary,because of the apply of the strata stress source; Both the border edge of coal and rock seam and boundary of hydraulic flushing in hole need to inspect the change of stress,strain, displacement,also they need to set as free boundary.

(3) Roller boundary.The lateral pressure on coal is transmited from infinity,it is set as roller boundary.

The definite condition of gas seepage module:

The initial conditions: The initial conditions of gas flow field of gas-saturated coal is that the primitive gas flow field is set the primitive gas pressure constantly at the zero-time of model calculation:

$$P(x,y,z,t)\big|_{t=0} = P(x,y,z,0)$$

The boundary conditions:

(1) First species of boundary conditions:the boundary pressure is constant,the pressure gradient is zero.

(2) Second species of boundary conditions:the pressure within the scope of hydraulic flushing in hole is negative pressure constantly,in this simulation the value is -30Kpa.

(3)Third species of boundary conditions:the surrounding rock of roof-floor of coal seam is gas-tight,the boundary of gas flow is zero.

The weight of washout coal of single borehole is set as 0.5t/m,1.0t/m,1.5t/m, the radius of the hole expand respectively for 0.34m,0.48m,0.58m,adopts COMSOL-Multiphysics software simulates the stress condition of borehole with different weight of washed coal.

The borehole radius of drainage is simulated with the weight of washout coal which set as 0.5t/m,1.0t/m,1.5t/m,the efficient influence radium is set with the condition of gas pressure reduces to 0.74Mpa. As shown in figure 3-5.The figures show that the gas pressure of borehole with the weight of washed coal 0.5t/m reduces below 0.74Mpa at the distance of 4.9m from wall of hole,the efficient influence radium is 4.9m, the efficient influence radium of the weight of washed coal 1.0t/m is 6.4m, the efficient influence radium of the weight of washed coal 1.5t/m is 7.4m.As the weight of washed coal increase,the efficient influence radium of borehole increases gradually.

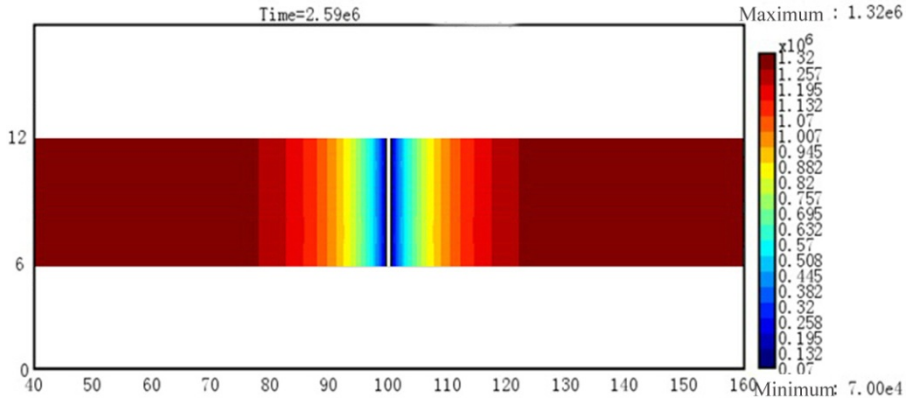


Figure 3. The distribution diagram of gas pressure while the amount of expulsion coal is 0. 5t/m

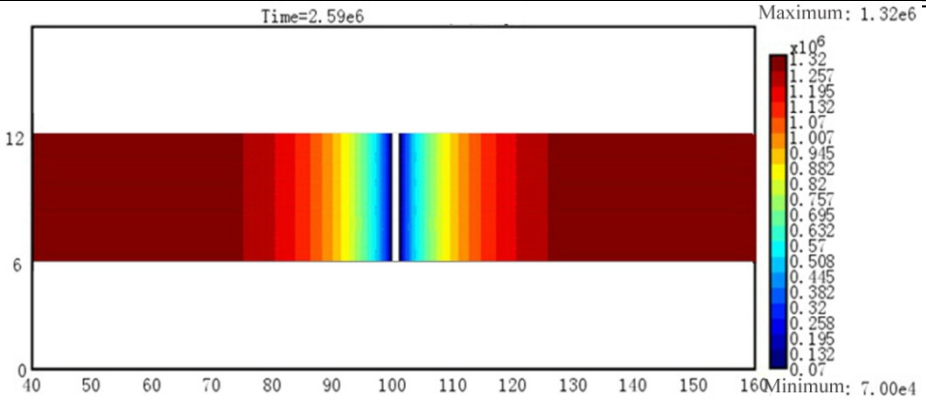


Figure 4. The distribution diagram of gas pressure while the amount of expulsion coal is 1.0t/m

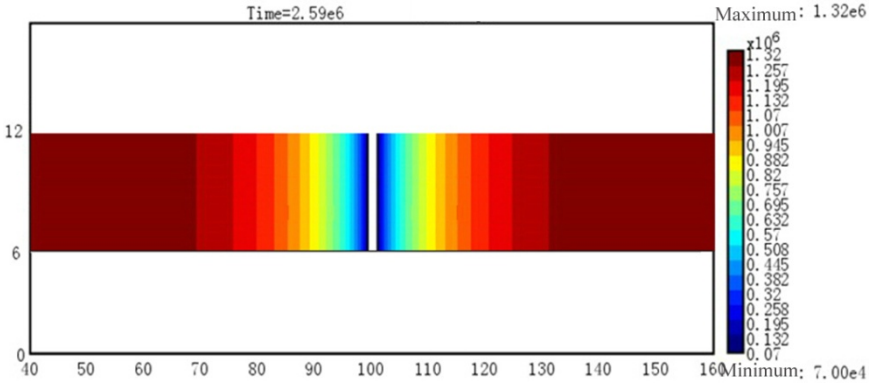


Figure 5. The distribution diagram of gas pressure while the amount of expulsion coal is 1.5t/m

These results indicate that when the extraction time is 30 days, the effective influential radius raises along with the amount of coal rushed out each meter. The rate of effective influential radius reaches the maximum when the amount of coal rushed out each meter between 0.5t/m and 1t/m, others are relatively low.It shows that when the amount of coal rushed out is 1t/m,the effective influential radius improve significantly, consistant with the previous conlusion that when the amount of coal rushed out each meter is above 0.5t/m, the punching effect is more effective. Meanwhile, considering the punching effect improves smaller and the worker's labor increases a lot when the amount of rushed coal is more than 1t/m, considering the punching effect is not obvious when the amount of rushed coal is less than 0.5t/m,so the amount of rushed coal each meter is 1t or slightly more than 1t is feasible for standard rushed coal.

Because the stress of coal seam is large, the coal body is soft, the diameter of drilling hole changes,the drilling hole shrinks and pressure range largens with time. Due to the rheological characteristics of coal, coal around the drilling hole moves toward the hole and blocks the hole with time. Once the drilling hole blocked, the channel of methane gas transport is blocked, although the permeability of coal around the drilling hole increases significantly, the concentration of methane gas drainage is very low, which is consistant with the drainage practice.

Considering the great change of coal seam thickness and the inhomogeneity of drilling hole, the drainage radius times 0.8, place the drilling hole according to the $\sqrt{2}r$ separation distance, along with the numerical simulation of decompressing and yield zone, the hydraulic flushing influential radius designated as 4.5m is more reasonable.

From the above, for the coal seam mining condition, when the rushed coal of each hole is 1t/m,along with the drainage practice effection, hydraulic flushing influential radius designated as 4.5m is feasible.

3 Field test of hydraulic flushing influential radius

This text used the pressure method to determine the effective radius of influence of hydraulic punching. The basis of pressure method to determine the effective radius is: hydraulic punching bit jet of high pressure water jet washing coal wall, lead to the coal seam fissure expands, links the methane gas transport channel, great amount of methane gas releases through the channel, pressure of methane declines,so the change of methane pressure and be used to determine the precision of previous hydraulic flushing influential radius. This text drilled three holes on the base board, the monitor hole between

the NO.1 peep hole and NO.2 peep hole, space the monitor hole 4.5m and 6m separately.

Measure the coal seam methane gas pressure before hydraulic flushing, the initial methane gas pressure is:0.85Mpa of NO.1 peep hole,0.83Mpa of NO.2 peep hole,0.80Mpa of monitor hole. Conduct the experiment until the methane gas pressure is stable. The methane gas pressure of measured hole is 0Mpa during hydraulic flushing, the pressure of NO.1 peep hole inclines to 0.35Mpa,indicating that the NO.1peep hole is within the hydraulic flushing influential radius, the pressure of NO.2 peep hole inclines to 0.75Mpa after hydraulic flushing, indicating the pressure relief effect is not obvious, the influence of hydraulic flushing is less. Above all, the conclusion of pressure method to determine numerical simulation indicates that to determine the hydraulic flushing effective influential radius of 4.5m is feasible for the coal mine, it can fully relief the pressure of coal seam within influential radius, stress declines effectively, coal seam permeability increases, provide the basis of determining the parameter of methane gas extraction hole arrangement, reduce the occurrence of the blank area, avoid the blindness of the measures, save the manpower and resource, have the practical implications.

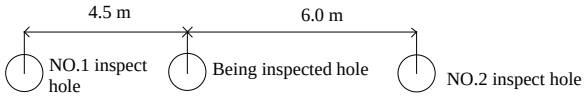


Figure 6. Field verification on influence radius of hydraulic borehole flushing

4 The integrated application of hydraulic flushing and "three-steps drainage method"

The coal of experiment coal mine is soft, the thickness of coal seam changes significantly, the coal seam has the ability to blowout, this text used the hydraulic flushing along with "three-steps drainage method" [13-14]proposed by Liu mingju and Hao fuchang to prevent the accident of coal and methane gas outburst and methane gas exceeding. First step, drainage in non-pressure released zone, constructed the drilling hole on the baseboard of coal seam, using hydraulic punching pressure relief anti-reflection technology, this measure eliminates the outburst danger of the working face; Second step, drainage in pressure released zone formed ahead of working face, drainage the methane though drill hole, this measure could prevent gas outburst and transfinite accidents; Third step, drainage the goaf, after finishing the face mining, drainage the methane gas of goaf through drill hole, prevent methane flow back into working face goaf.

5 Effect analysis

Statistics on hydraulic punching hole is shown in fig.7, use hydraulic punching as outburst prevention measures effect is more obvious, accumulated statistics of coal is 371t, the quantity of coal puckering is 4t at least and 10t at most, the average value is 6.3t, most quantity of coal puckering is between 5-8t. According to the amount of coal rushed out ,the accumulated volume of punching is 265m^3, the average value is 4.49m^3, equivalents to the diameter of 75 mm hole enlarge to 513 mm holes, coal around the drilled hole has pressure relief completely, enlarge the coal seam fissure, improve the permeability of coal seam, discharge the methane gas in coal seam completely, relief the methane gas expansion energy accumulated in coal seam.

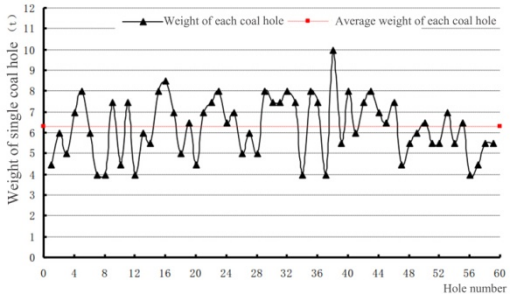


Figure 7. Hydraulic punching the hole puckering landings

Drainage flushing relief stress around the drill hole through flushing out a certain amount of coal and discharge a certain amount of methane gas, relif the stress of surrounded coal in various extent, improves the permeability of coal seam, enlarges the amount of methane naturally releases and drainage out, working face gas emission decreased greatly, drill borehole down the coal seam upward and downward the working face after which, no orifice or stick happens, when the borehole drilled to the predetermined depth, it erases the danger of the blank area in the middle of working face. To verify the effective of this plan, chose the proper place, remeasure the methane gas in the blank area, results are shown in table.8.

Table 8. Working face of coal seam gas pressure after punching indirect test table

Sampling place	Mad(%)	Aad(%)	V_f(%)	a (m^3/t)	b (Mpa^{-1})	Residual gas pressure (MPa)
1	0.43	12.07	18.17	30.174	0.328	0.31
2	0.21	10.28	17.83	30.174	0.328	0.69
3	0.44	9.97	19.89	30.174	0.328	0.56
4	0.22	37.24	15.39	30.174	0.328	0.27

Conclusions are as follows: when the gas pressure is between 0.3Mpa and 0.7Mpa, average of 0.5Mpa, far below the average gas pressure of 0.9Mpa previously, coal seam gas pressure is below 0.74Mpa after punching. Coal seam gas content is between 1.8 and 5.9m^3/t, the average is 3.8m^3/t, compared to the previous measures, the amount declines 41%, indicate that hydraulic flushing is a proper measurement to relief pressure, increase permeability, intense discharge of gas.

6 Conclusions

This text analysed the hydraulic flushing measurement along with numerical simulation and field test, researched the mechanic of high pressure water flushing coal seam, through numerical simulation and field test, determined the effective radius of coal mine hydraulic flushing, studied the measurement of hydraulic flushing along with "three-steps drainage method" to deal with gas problem, and investigate the results, reaches the previously setted purpose, conclusions are as follows:

(1)This text determined the water pressure as 18Mpa of hydraulic flushing through analyse the mechanical of high pressure punching breaking coal, can meat the requirement of measures and easy to technology implement.

(2)This text used numerical simulation software COMSOL-Multiphysics to simulate the stress condition in different amount of rushing coal, determined the hydraulic flushing effective radius is 4.5m in the rush out coal of 1t/m each hole.

(3)This text used hydraulic flushing effective experiment, take measurement of inspect the monitor hole gas pressure, verifies the numerical simulation, determined the hydraulic flushing influential radius is 4.5m.

(4)Combined the measurement of hydraulic flushing and previously "three-steps drainage method", used the rush out coal to verify the flushing effection, on average of 5-8t each borehole, used the remnants gas pressure and remnants gas content to verify the effection, remnants gas pressure and gas content inclines a lot compared to measurements taken before, it shows the hydraulic flushing is a effective measures.

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