

Production field numerical simulation and parameter optimization of Multi-point Hydraulic Fracturing coal seams¹

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Abstract

Hydraulic fracturing technology, as one of the irrigation measures to increase the coal seam permeability artificially, has its remarkable advantages. This paper mainly uses the methods of theoretical analysis, RFPA2D numerical simulation and field validation to study multi-point fracturing. It proved the reliability and accuracy of multi-point fracturing numerical simulation by comparing multi-point fracturing simulation results with multi-point fracturing field test results. At the same time, it optimized the process parameters of multi-point fracturing site through simulation. Taking the fracturing borehole in a mine's multi-point fracturing field test as the background, a conclusion was drawn from the multi-point fracturing simulations with different water point spacing that when the water point spacing is 3 meters, the fracturing effect is the best. The numerical simulation of optimization results provided a reference for the application and parameter choice of the underground coal mine multi-point hydraulic fracturing technology and thereby succeeded in improving the fracturing effect and gas extraction rate to the greatest degree. This is of great practical significance to the coal mine safety production and the increase of economic benefits.

Key words : MULTI-POINT FRACTURING, NUMERICAL SIMULATION, FIELD SIMULATION, PARAMETER OPTIMIZATION, COALMINE SAFETY

As a regional coal seam removing outburst measure, hydraulic fracturing technology has been widely used in many coal mines with its simple construction technology and remarkable pressure relief and anti-reflection effect. Hydraulic fracturing technology is the drilling operation of the water layer or bedding of the coal seam construction. High pressure water is injected into those boreholes and then the borehole wall begins to fracture under the effect of high pressure water. At the same time, the high pressure water produces a kind of internal water pressure on the fracture wall, which prompts the fractures to expand and extend continuously to finally form an interpenetrating fracture system. As this happens, the coal seam permeability increases.

Meanwhile, a small displacement of coal mass occurs under the effect of high pressure water, making the coal seam get the pressure relief within a certain range. Thus gas potential energy and elastic energy get released and the gas drainage is easier so as to greatly reduce the gas pressure and content and to ultimately weaken or eliminate the danger of coal seam outburst^[1].

The introduction of hydraulic fracturing anti-reflection technology into coal mine first started in the former Soviet Union and it was Ma Kaiyev Coal Safety Scientific Research Institute that put forward this theory^[2]. As a pressure relief and anti-reflection technology, especially in underground coal mines, hydraulic fracturing developed slowly, and so far it

has not yet formed systemic technology and equipment . There are three main reasons^[3]: First, the hydraulic fracturing extrusion equipment cannot meet the technical requirements ; second , as China's coal mining depth deepens year by year , the coal seam fracture is easily to become closed again after fracturing ; third , there is no advanced theory to guide the development of fracturing technology , for the study of theory about hydraulic fracturing technology has not achieved big progress .

Since the hydraulic fracturing test is successful in the United States in 1940s , many countries have began to study hydraulic fracturing technology one and other . So far , many a kind of fracturing test has achieved success . Among them are such common technology as re-fracturing technology^[4], multi-layer and multi-fracture fracturing technology , directional fracturing technology^[5] etc.; new fracturing technology as water fracturing technology , floating proppant fracturing technology , tip screen out and fracture length control fracturing technology , hydraulic jetting layer-by-layer fracturing technology^[4] .

At present, many coal mine enterprises in China have got good results in the application of hydraulic fracturing technology and they have accumulated a lot of experience . Sun Bingxing^[6] et al. carried out the hydraulic fracturing anti-reflection test and the result showed that after fracturing , the borehole's natural gas flow increased by more than 127.6 times , and the influence radius of borehole's strike could reach over 50 times. Tan Daoxiong^[7] et al. took hydraulic fracturing measures in Tan Jiachong Mine ventilated gateway of 2264-1N-S coal face , the single-bore gas-draining quantity and drainage concentration were improved greatly . Moreover , the attenuation coefficient of coal seam gas flow was smaller . Li Quanguai^[8] et al . carried out hydraulic fracturing in Daxing Mine Sv719 working face by drilling borehole down the seam , and the result showed that gas-draining quantity increased by 7.2 times and the permeability coefficient in coal seam of the impact region was improved by 79-272 times . Xu Youping^[9] et al . conducted the directional hydraulic fracturing test in Pingdingshan Coal Group No. 12 Mine Ji-15-31010 working face , and they drew these conclusions : Under 27Mpa hydraulic pressure , single-bore fracturing influence radius was 6m ; single-bore gas-draining concentration increased by 80% ; average gas flow increased 382% ; the test produced remarkable effects .

Nonetheless , in some geological and coal seam occurrence conditions , the effect of conventional hydraulic fracturing is not satisfactory . At this time , it is necessary to study the new fracturing technology—

multi-point fracturing technology , so as to better enhance the fracturing effect in coal seam .

In the field where hydraulic fracturing is carried out in coal strata with conventional hydraulic fracturing technology , there are several steps : First , conduct the fracturing drilling in the hydraulic fracture bore ; second , seal the hole , and meanwhile directly inject high pressure water into the hole with fracturing equipment to fracture the whole borehole . At this time , the effective range of hydraulic pressure is a cylinder with a length ranging from several meters to tens of meters , and it covers the area from the hole packer to the hole bottom . In the process of injection , water may leak badly from the borehole wall because of the big effective action area of water . In order to guarantee enough hydraulic pressure and flow rate , the requirement of fracturing equipment will be more strict . In the meantime , when the fracturing drilling is in certain stress environment , the stress concentration may easily occur on both sides of the drilling , and under the action of hydraulic pressure , the situation where both sides of the drilling fracture with no fractures in the middle may possibly occur . If it occurs , the pressure relief and anti-reflection effect of hydraulic will be influenced .

When the fracturing drilling is divided into several segments , each segment is set up with a water point , and every two water points are connected by a special hole packer , concentrate hydraulic pressure on these points to conduct the fracturing process , that is , shift the action of hydraulic pressure from one surface to several points . At this time , since the points of action are evenly distributed within the fracturing drilling , the central water point will force the coal seam in the middle part of the drilling to fracture so as to increase fracturing influence and reduce blank zone . Meanwhile , because of the smaller water point, a small water flow can achieve the ideal fracturing effect . This reduces the requirement of fracturing equipment, and thus the size of equipment is greatly reduced , which makes it more suitable for use in the limited space of underground roadways^[10-11] . This is what multi-point hydraulic fracturing about . The borehole wall stress analysis of conventional surface fracturing and multi-point fracturing is as Figure 1 in the following :

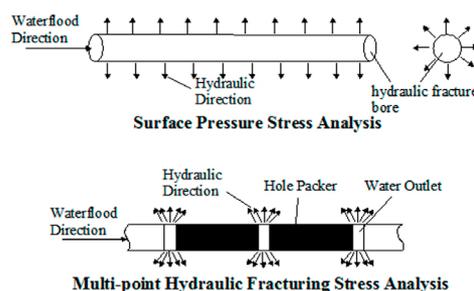


Figure 1. Multi-point Hydraulic fracturing borehole wall stress analysis

2. General situation of the experimental mine

The experimental mine studied was founded in 2007 with a target annual output of 2.4 million tons, and it is a large modern coal mine. With a mining area of 37.89 km², the vertical shaft of this mine exploits the Chengzhihe River coal-bearing strata of late Jurassic epoch. There are more than 40 coal seams in the strata, among which 15 can be mined and the average thickness of the minable seam is 15.6 m.

The construction site of multi-point hydraulic fracturing is located in No.4 right 3 roadway west 2 mining area of the coal mine. As shown in Figure 2, it is the ventilation roadway of the working face which has not been mined yet. The thickness of the coal seam here is 2.8 m. Multi-point fracturing is conducted

by drilling from the ventilation roadway to the coal seam. There are altogether three fracturing boreholes and four control holes in this fracturing. The spacing between each fracturing borehole and each inspection hole is 5 m. The fracturing drilling layout is shown in Figure 3.

The main equipment employed in this multi-point fracturing test in the coal mine studied includes high pressure water injection pumps, hole packers, high-pressure water hoses, injectors etc. The high-pressure sealing capsule is used to seal both sides of the water point within the drilling. The pressure in it is always 1Mpa higher than the water injected into the drilling and thus its sealing effect is quite good.

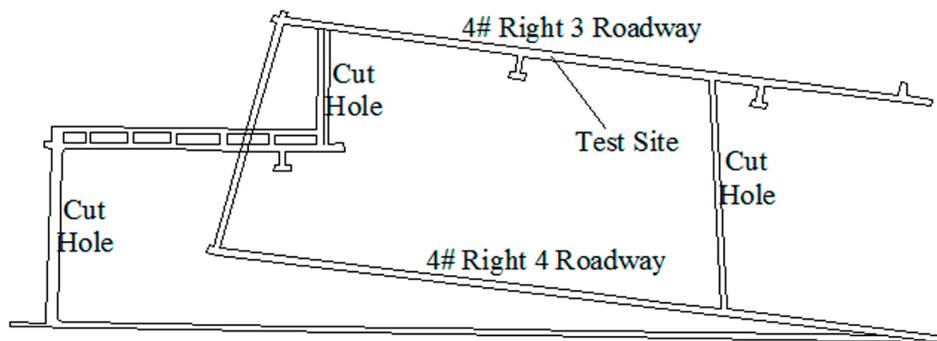


Figure 2. Multi-point hydraulic fracturing test site

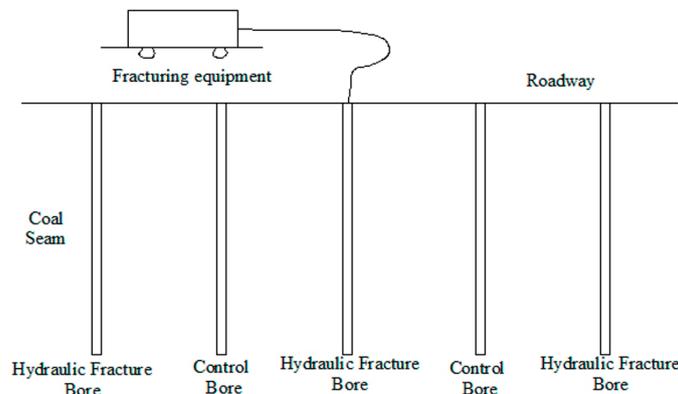


Figure 3. Fracturing drilling layout plan

3. Fracturing process and results

No. 6 bore is taken as an example to analyze the fracturing. The length of No. 6 borehole is 18 m and its diameter is 75mm. The spacing between it and neighboring control holes is always 5 m. The control hole is mainly used to study the fracturing effect and its radius. During the fracturing process, the fracturing results can be evaluated on the basis that whether there is water coming out and how much it comes out. During the construction, there are three water points within No. 6 borehole with a spacing of 2m. After the installation of equipment, the high pressure hydraulic device is connected to fracture the coal seam.

In the process of fracturing, when the fracturing pressure reaches 15Mpa, water begins to come out from the control holes next to No. 6 borehole. When the hydraulic pressure reaches 17.6Mpa, it stops to increase and begins to drop. At this moment, the fracturing ends. It can be seen that the influence radius of the fracturing is at least 5m, and the fracturing pressure is 15—17.6Mpa. After the fracturing, gas drainage of the coal seam is carried out. The result shows that single-hole gas-draining quantity increases 4 times and its concentration increases 3 times than before.

4. Field numerical simulation of multi-point fracturing

In order to verify the reliability and fidelity of the simulation result of multi-point hydraulic fracturing technology, and provide a reference for the parameter optimization of field hydraulic fracturing, in the following, RFPA2D numerical simulation will be conducted by using the construction parameters of the multi-point hydraulic fracturing site in the coal mine. The processes and results of simulation and field construction can be used to analyze the similarities and differences between them.

4.1 Model building

Based on the field test conditions of multi-point hydraulic fracturing, the size of the fracturing simulation is designed as 20m*30m, and altogether it is divided into 200*300 primitives. The length of fracturing drilling is 18m. Three water points are there and the water point spacing is 2m. A hole packer is set in the bottom of the borehole. The initial loading hydraulic pressure is 12Mpa, and 0.2Mpa is loaded every step. The specific model parameters are shown in table 1.

4.2 Fracturing results

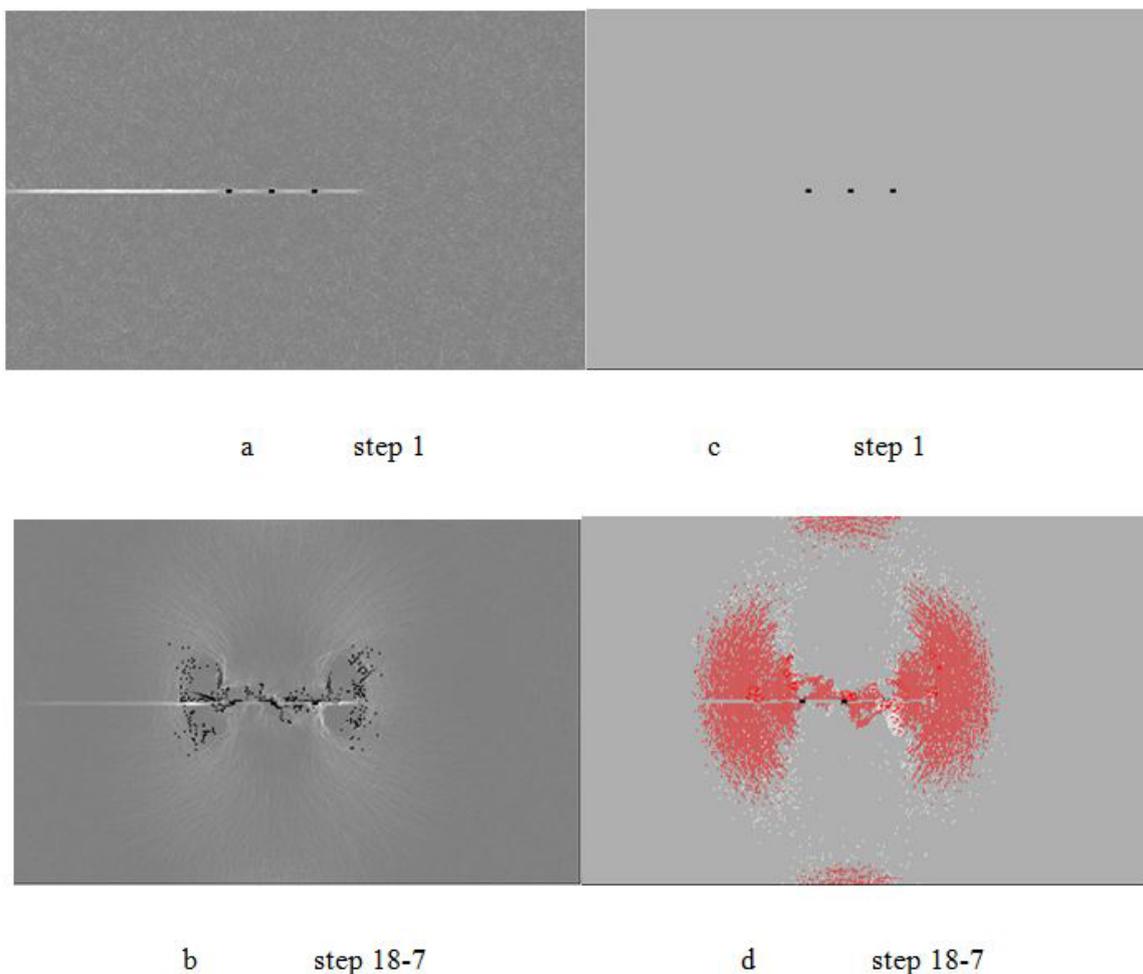


Figure 4. Simulation results live multi-point fracturing

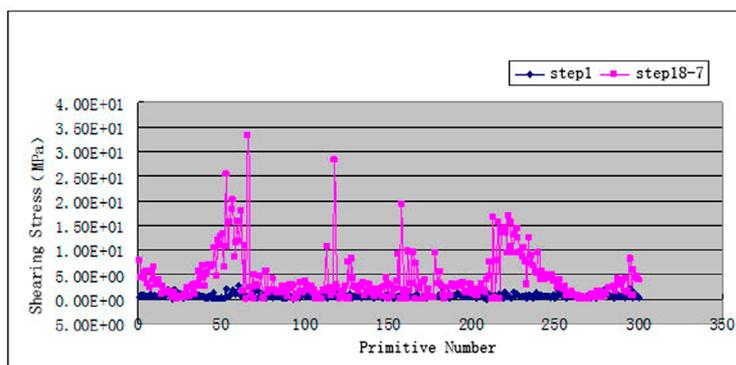


Figure 5. Shear stress field simulation of multi-fracturing changes

Figure 4 shows the damage by shearing stress in the process of field multi-point fracturing numerical simulation . As shown in Figure 4-b , when the spacing between two water points is 2m , the visible fracture in vertical drilling direction of the multi-point fracturing can extend as far as 3.5m away from the drilling . Figure 4-d shows that when the damage radius of coal seam is 6.5m , the coal seam will completely fracture at 18-7 step , and the hydraulic pressure is 15.6Mpa at this time .

Figure 5 shows the shear stress change in the process of field multi-point fracturing numerical simulation . It can be seen that at 18-7 step of the fracturing , on both sides of the model , the phenomenon of stress rising and concentration occurs in the position far from water points , and in the middle part of the model , there is a relatively smooth change of the coal seam except that the shear stress above the drilling increases dramatically . Based on the shear stress , the analysis shows that the fractures around the first and third water point on the model extend in the direction of the four angles of the model , and the influence radius along the drilling is fairly the same as that of the vertical direction . In addition , the coal seam is extruded to the left and right when the fractures extend to the top left and top right , causing the shear stress of extrusion field to increase . However , as the fractures near the top of the second water point in the middle part have not extend much , in addition to the position above the water point , the shear stress of other positions changes a little .

Compared with field test results , the numerical simulation results show that the radius of visible fractures is 3.5m , the damage radius is 6-6.5m and the fracturing influence radius can be 5m or even more than 5m , which overlaps with field test results . Besides , as for the pressure , the complete fracturing in the simulation requires a pressure of 15.6Mpa , which is within 15—17.6Mpa , a scope of fracturing pressure obtained in field test . Therefore , these numerical simulation results of field multi-point fracturing are reliable and overlap with field test results .

5. Multi-point fracturing simulation of field water point spacing optimization

5.1 Coal seam damage area simulation of different water point spacing

According to the multi-point fracturing simulation parameters of hydraulic fracturing simulation site in the coal mine studied , water point spacing can be adjusted so as to simulate the fracturing effect of No . 6 borehole when the size of water point is different . This can provide a reference for fracturing technology parameter optimization . The water point spacing is designed as 1m , 3m and 4m , and after fracturing , the results are analyzed in comparison with those of spacing of 2m . During the fracturing process , except for different water point spacing , other parameters , hydraulic pressure and boundary conditions are all the same .

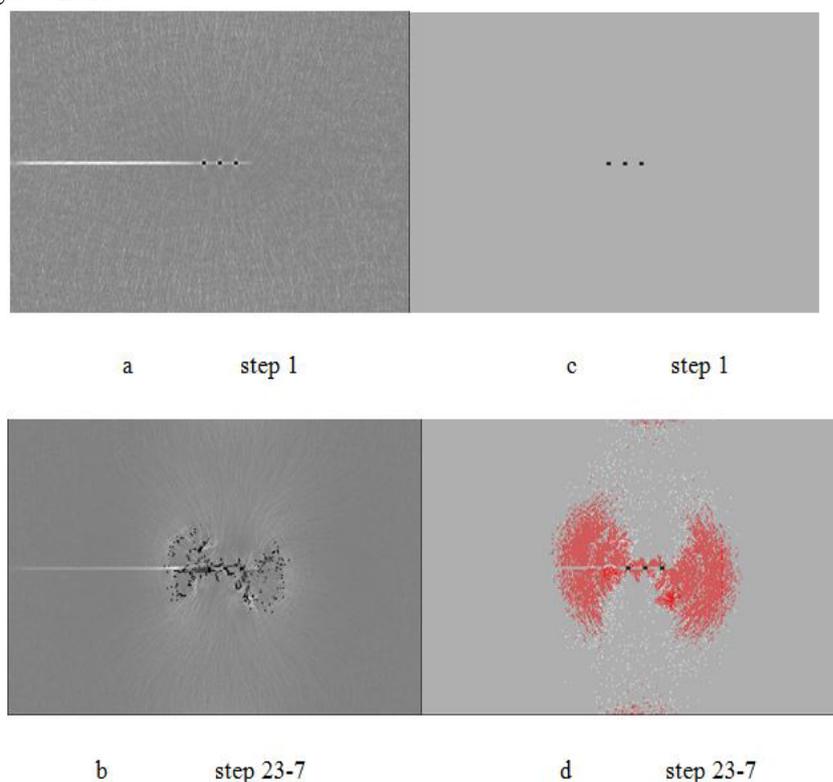


Figure 6. Fracturing simulation results when the water point spacing of 1m

Figure 6 shows the shear stress and damage diagrams in the process of multi-point fracturing when the water point spacing is 1m . As shown in the diagrams , at 23-7 step of the fracturing , the model completely fractures , and the hydraulic pressure is 16.6Mpa at this time . Figure 6-b shows that after

model fracturing , the visible fractures can extend 3.2m in the vertical drilling direction , and the damaged coal seam can extend as far as 5.5m . The fractures mainly extend in the direction of the four angles of the model , and the fractures in the middle part of the water point do not develop well .

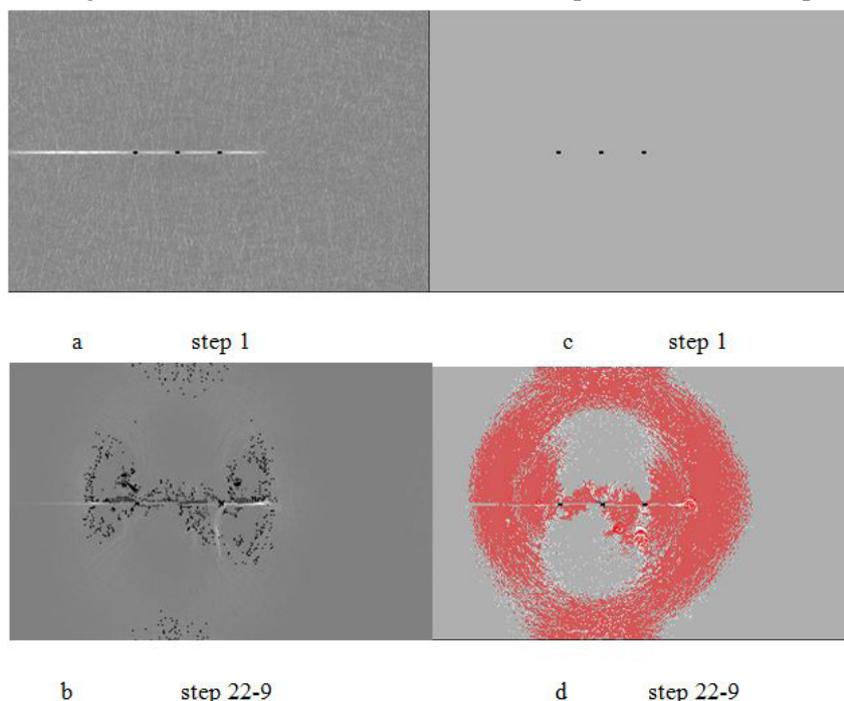


Figure 7. Fracturing simulation results when the water point spacing of 3m

Figure 7 shows the shear stress and damage diagrams in the process of multi-point fracturing when the water point spacing is 3m . At 22-9 step of the model fracturing , when the hydraulic pressure reaches 16.4Mpa , the coal seam completely fractures . Shear stress diagram b and damage diagram d show that the visible fractures after fracturing can extend 5m in vertical drilling direction . In the damage dia-

gram , after removing the damaged seam because of the confining pressure effect on the model boundary , the coal seam damaged by fracturing effect is about 8m , and the fractures also mainly extend in the direction of the four angles . Furthermore , the fractures of coal seam in the middle part of the water point have also developed .

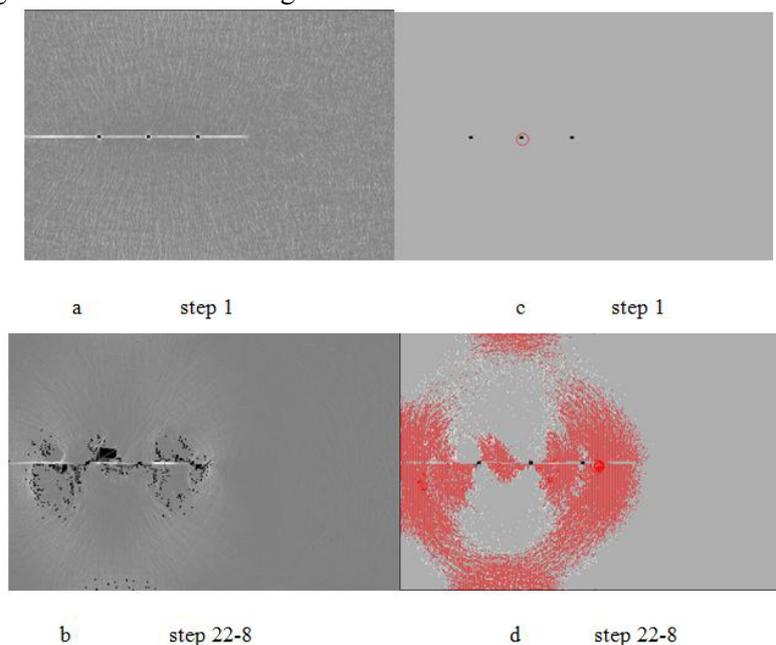


Figure 8. Fracturing simulation results when the water point spacing of 4m

Figure 8 shows the shear stress and damage diagrams in the process of multi-point fracturing when the water point spacing is 4m . At 22-8 step of the fracturing , when the hydraulic pressure is 16.4Mpa , the model completely fractures . Shear stress diagram b shows that in the process of fracturing , the visible fractures can extend as far as 4.7m in vertical drilling direction . In the diagram , after removing the damaged seam caused by confining pressure effect , the

coal seam damaged by fracturing effect is up to 8m. In addition , the fractures of central water point in the model develop poorly , and the fractures on both sides of the drilling develop unevenly .

5.2 Coal seam fracturing results comparing different water point spacing

Table 2 is drawn by gathering fracturing results of different water point spacing . Figure 9 is made by comparing the shear stress change diagrams .

Table 2. Multi-fracturing simulation results comparing different water point spacing

| Water point spacing (m) | Cracking pressure (Mpa) | Visible fracture radius (m) | Damage radius (m) |
|-------------------------|-------------------------|-----------------------------|-------------------|
| 1 | 16.6 | 3.2 | 5.5 |
| 2 | 15.6 | 3.5 | 6.5 |
| 3 | 16.4 | 5 | 8 |
| 4 | 16.4 | 4.7 | 8 |

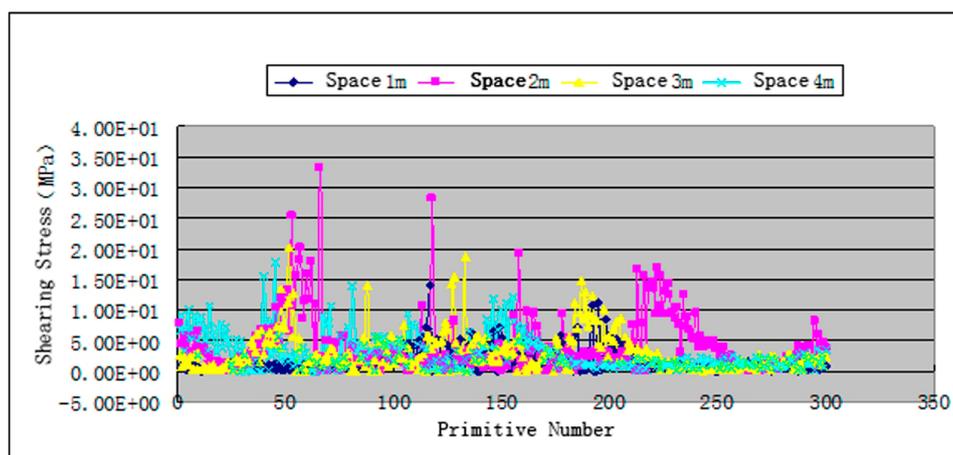


Figure 9. With water point spacing of multi-point change in the shear stress fracturing simulation comparison chart

As shown in Table 2 , the comparative analysis of multi-point fracturing simulation results of different water point spacing shows that among these four different water point spacing , the fracturing pressure of three has little difference except that when the spacing is 2m , the pressure is lower . Besides , the fracturing pressure of four spacing is always within 15—17.6Mpa , a scope of fracturing pressure obtained in field test . The comparison between the radius of fracture and damage influence shows that both radiuses increase with the increase of water point spacing , and that when the spacing is 3m or 4m , they are almost the same . However , when the water point spacing is 4m , the radiuses of visible fractures are smaller , and the fractures on both sides of the drilling develop unevenly , that is , they develop better on one end

than the other . Meanwhile , the fractures of coal seam in the middle part of the drilling develop poorly. Therefore , when the spacing is 3m rather than 4m , the fracturing effect is better .

According to the shear stress change in the model fracturing process with various water point spacing , when the spacing is 1m , the change in the shear stress of model is minimal , and because the spacing is small and drillings are intensive , shear stress in the middle of model increases a little and on both sides of the coal seam , it changes little . When the spacing is 2m , the shear stress of coal seam changes the most dramatically . The shear stress of coal seam on the left end of the first water point and the right end of the third increases most , which corresponds to the above extension of fractures in the shear stress diagram.

When the spacing is 3m or 4m , the scope of shear stress change of coal seam is large , and in general , the change is smooth . When the spacing is 4m , the shear stress of most coal seam on the right side of model remains unchanged to some degree as a result of the poor extension of the fractures to the right side .

After comparing the model fracturing results of different water point spacing , a conclusion can be reached :Based on the practical situation of hydraulic fracturing of the mine , when water point spacing is 3m , the fracturing effect is best .

6. Conclusion

(1)The multi-point hydraulic fracturing test situation of the coal mine studied is introduced , and after multi-point hydraulic fracturing , gas-draining effect of the coal seam is remarkable .

(2)Based on the field parameters of multi-point fracturing of the mine , a simulation is conducted by using RFPA2D software , and the conclusion includes : In the simulation , the radius of visible fractures is 3.5m ; the damage radius of coal seam is 6.5m ; the fracturing influence radius definitely can reach 5m which is a limit in field application ; the hydraulic pressure for a complete fracturing is 15.6Mpa , which is within 15—17.6Mpa , a scope obtained in field test , and the simulation results are consistent with those of field test .

(3)Taking No. 6 borehole of the multi-point fracturing test field as the background , the multi-point fracturing simulation of different water point spacing by using RFPA2D software comes to a conclusion that when the spacing is 3m , fracturing effect is best and can provide a reference for field multi-point fracturing process optimization .

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