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The Pressure Relief and Permeability Increase Mechanism of Crossing-Layers Directional Hydraulic Fracturing and Its Application

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Abstract

In order to reduce roof-floor blind area of hydrofracture in underground mines, expand influenced range of fracturing, improve the effect of hydrofracture, a pressure relief and permeability increase model of hydraulic fracturing was built on the basis of analysing the mechanism of crack initiation and the characteristics of fracture development. After discussing the mechanism of directional hydraulic fracturing and carrying out related numerical simulation, a directional hydraulic fracturing technique was proposed. The coal fracture development distribution rule in the process of directional hydraulic fracturing was analysed, and the directional hydraulic fracturing technique was applied in the F_{15}-31010 mining workface of The Twelfth Coal of Pingdingshan Coal Mining Group. The results show that single-drill hole fracturing effective radius rise to 6m under the pressure of 27Mpa, which is 3-5 times more than before, and the average concentration of single-drill hole gas drainage promote to 87.5%, average flow up 55.6% than no-directional hydraulic fracturing. All these suggest that the technology obtains remarkable effect, and has a high application value.

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Keywords: cross layer; directional hydraulic fracturing; pressure relief and permeability increase; RFPA2D-Flow software

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1. Introduction

It has been development for half a century since hydraulic fracturing technology successfully tested in 1947. As an effective technical measure to increase production, it has been widely used for the exploitation of low penetrating oil and gas pool [1-4]. However, in the condition of ground drilling, the study of hydraulic fracturing is limited to the exploitation of oil, oil-gas reservoir, gas reservoir and geothermal well resource.

In coal mine, the Soviet Union started to carried on the test of hydraulic fracturing underground in the 1960s .15 mine field in Carla Ian had been conducted coal seam hydraulic fracturing trial. Hydraulic fracturing had be tested ground and underground in Baishahongwei coal mine, Yangquan coal mine, Fushun north wind Wells, Jiaozuozhongma coal mine in our country since 1970. Some effects were achieved and some experience was summed up [5].

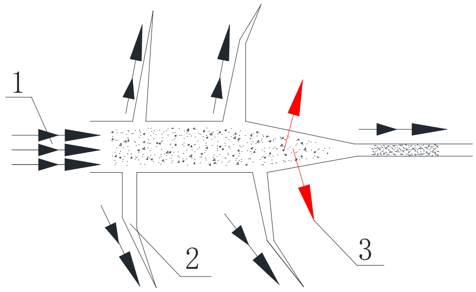
At present, the study of hydraulic fracturing, with a relative consummation theory, is mainly aimed at petroleum reservoir; nevertheless, there is an essential distinction between coal seam and petroleum reservoir. Along with the increase of coal mining depth, the coal seam gas permeability is lower. In view of this situation, it causes some scholars' attention in recent years that using hydraulic fracturing technology improves the air permeability of coal seam. Du Chunzhi [6], who depended on maximum tensile stress criteria, given the stress condition of fracture extension level of coal seam, and then analyzed the stress condition of space wall fracture extension .There was a narrow limitation for the model because it based on single creak. Zhang Guohua [7-9], who accorded to circular hole model, did some theory formula works on stress state of arbitrary point around drilling hole, and profitably discussed the position of the crack initiation. Leng Xuefeng [10], who simulated the rupture and instability of rock under the action of hydrodynamic pressure, contrasted and analyzed the influence of different homogeneous degree of rock to the process of hydraulic fracturing. According to the characteristics of the coal mass, the author researched on hydraulic fracturing crack mechanism and crack propagation law of coal seam, on the basis of which, proposed directional hydraulic fracturing technology, established numerical model to simulate the crack growth rule of directional hydraulic fracturing and applied the conclusion to worksite, achieved a nice effect.

2. The Permeability Increase Mechanism of Hydraulic Fracturing

2.1. Fracturing Mechanism of Cross Layer Hole

Coal is porous medium, and coal contains abundant native fracture. Under the action of pump pressure, the water of fracturing hole come into the coal layer, which has an effect on the bedding surface, native fracture, new fracture and fissure at all levels. Along with injection water pressure is greater than seepage water pressure, the internal water pressure which act at weaken surface makes it rupture, and then macro fracture is formed. At the same time, the press water enters the fracture. With the process going on, fissure damage variable increases, causing the growth, expansion and extension of secondary weak plan and the next weak plan. The porosity of wet coal raise and wet coal is filled with high pressure water. In the non-wetting coal, with the pressure going up, the coal is compressed, damaged, and also along with fissures. As a result, coal seam is compacted whose porosity decrease. For the heterogeneity and stress non-balance distribution in coal body, fissure expand inhomogeneous intermittent, the path is winding, accompanied by fork and kink. In the continuous process of fracturing, fissure is gradually interconnected with each other and develops into fracture network system, causing coal seam fracturing decomposition.

In the process of fracturing, each fracturing reinjection will certainly give rise to tensile stress at the normal direction of the weak plane. As the width and fracturing effect is greater than before, internal water pressure of weak plane will continue to increase, then normal tensile stress also increase .As the normal tensile stress is up to the prerequisite that can make secondary weak plane starting creak, adjacent secondary weak plane will start creak and then water enters it. The process is as the same as the first level weak plane, as shown in figure 1. In accordance with this law, it develops continuously, and water enters tiny fracture system of the coal.



1- High pressure water; 2-Secondary weak plane; 3-Tensile stress

Fig.1. Fracture propagation of secondary weak plane

2.2. Directional Hydraulic Fracturing Fracture Extension and Permeability Increase Mechanism

On the basis of the fact that fracture first appear at weak plane, we put forward directional hydraulic fracturing technology, namely, by the way of increasing the number of control hole in order to create weak plane and guiding the fissure, making good use of the hydrofracture energy to relief pressure and increase permeability, eliminating outburst, as shown in figure 2.

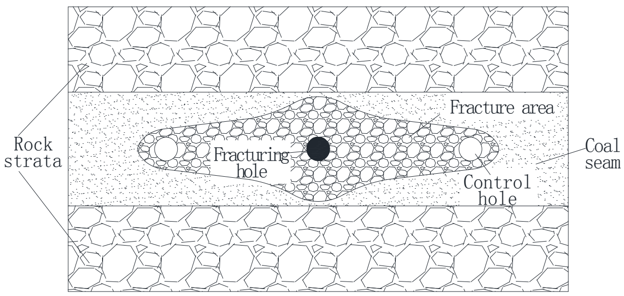


Fig.2. Fracture extension of directional hydraulic fracturing

In the process of drilling control hole, bit disturb the coal mass constantly, stress distribution of the surrounding rock changes, and finally develop into fracture zone, plastic zone, elastic zone and original rock stress area. The coal of fracture zone and plastic zone has been damaged, constituting macro fracture zone with columnar divergent distribution. With the increasing of the pump pressure, elastic zone and macro fracture zone also extend. When elastic zone of fracturing hole extends to the elastic zone of control hole, fissure thread together between fracturing hole and control holes, under persistent fracturing, fissure expand continuously. Stress concentration regions also transfer in the direction of away drilling hole. At the same time, coal flows deformation to fracturing hole, and distressed zone turns into flat, internal generating more fractures.

Directional hydraulic fracturing contributes to the full development of coal fracture between control hole and fracturing hole, forms stereo fissure nets, and thread together. At the same time, crustal stress fully release in the process of fracture production and coal rheology. Peak stresses between boreholes decreases, air permeability improves. We use networking extraction to make pressure relief and permeability increase

3. Numerical Simulation Analysis of Directional Hydraulic Fracturing

RFPA system is a numerical experiment tool that simulates the destroying process of coal and rock. As the same as other existing gradually destroys model, the analysing process includes stress analysis and the gradual damage analysis, etc. The biggest feature of the software is that by introducing the heterogeneity of material, the damage parameter and seepage-stress-damage analysis element, continuum mechanics analysis method can be used for treatment of a physical media problem. This is a new type of numerical experiments analysis method, and provides more effective and convenient analysis tool for coupling the destruction of the rock and flow-solid

3.1. The Establishment of the Pressure Relief and Permeability Increase Hydraulic Fracturing Model

In order to research the law of water injection pressure, burst pressure and the stress and strain rule around drilling, we researched the single hole unidirectional hydraulic fracturing first. Taking Pingmei group twelve ore 31010 face in F_{15} as the prototype research model, the simulated result would be contrasted with the application result in this working face. The F15 coal seam is about 4m thick and the mining faces elevation is 720-770 m. The coal strata of mechanical parameters are shown as table 1. Coal rock layers of material properties follow the Weibull distribution, stress is analyzed with finite element method and the yield principle employ the revise coulomb criterion.

It is regarded as 2D, building a plane mechanical strain model. The model forced about 16 MPa from the vertical stress and 22.4 MPa from the horizontal stress according to the measurement results underground. The whole model divided 400 x 400 units and the numerical model shows in figure 3 below. Its gas initial pressure is 2.85 MPa. The initial water injection pressure is 1 MPa, each step increments 0.5 MPa, a total of 60 operation step.

Table 1 Physical parameters of coal and rock

Mechanics and seepage parameter	Coal seam	Rock stratum
Homogeneous degree	2	4
Mean of elastic modulus E_0/gpa	4.8	65.0
Mean of compressive strength σ_0/mpa	30	100
Poisson ratio μ	0.30	0.25
Friction angle /°	26	30
Pressure-tension ratio	20	10
Intensity attenuation coefficient B_s	0.1	0.3
Air permeability coefficient $m^2/(mpa^2 \cdot d)$	0.10	0.001
Gas content coefficient Aw	2.0	0.01
Liquid-solid coupling coefficient β	0.25	0.10

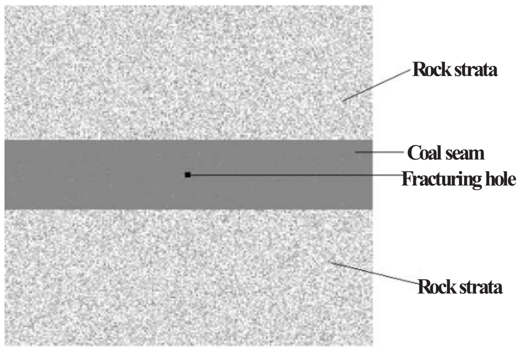
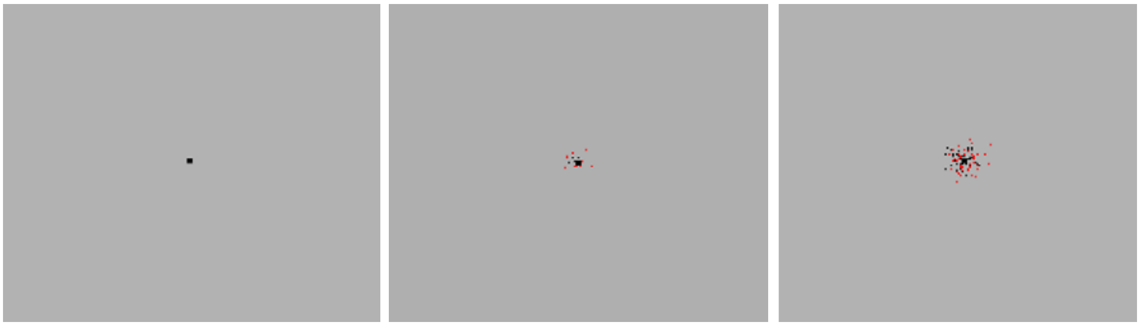


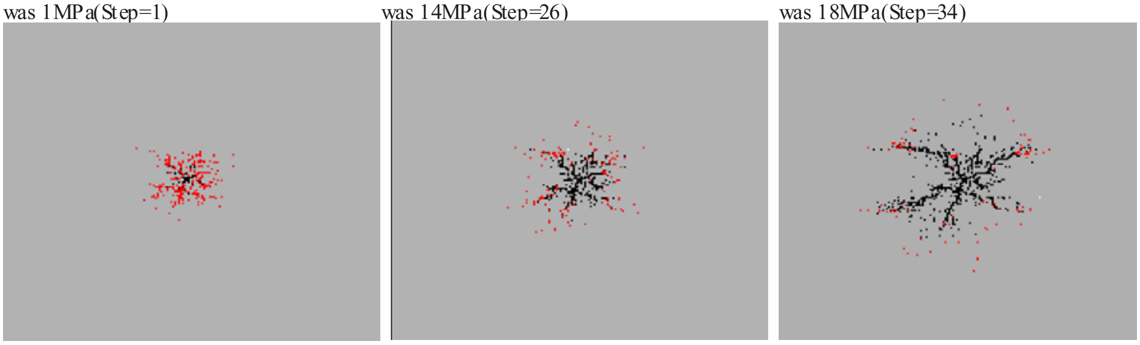
Fig.3. Model calculation of the single drilling hydraulic fracturing diagram

3.2. Numerical simulating the process of water injection rupturing the coal seam

In the acoustic emission diagram of RFPA2D-Flow, dots representative acoustic emission wave, where acoustic emissions happen, also said the fracture of the coal at this point.



(a) AE diagram when injection pressure was 1MPa(Step=1) (b) AE diagram when injection pressure was 14MPa(Step=26) (c) AE diagram when injection pressure was 18MPa(Step=34)



(d) AE diagram when injection pressure was 24MPa(Step=46) (e) AE diagram when injection pressure was 25MPa(Step=48) (f) AE diagram when injection pressure was 31MPa(Step=60)

Fig.4. AE diagram of fractrue initiation and extension during hydraulic fracturing

Exporting the data of RFPA2D-Flow system, we quantitatively analyzed AE counts and AE energy, and diagrammed AE counts, AE energy and AE accumulated energy.

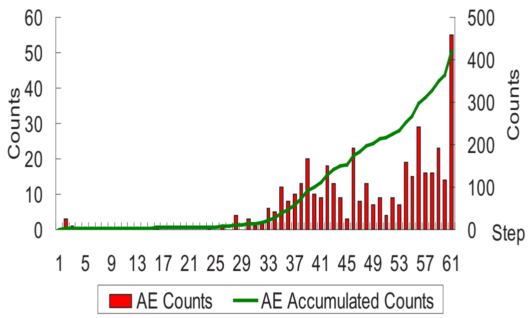


Fig.5. AE counts with load step

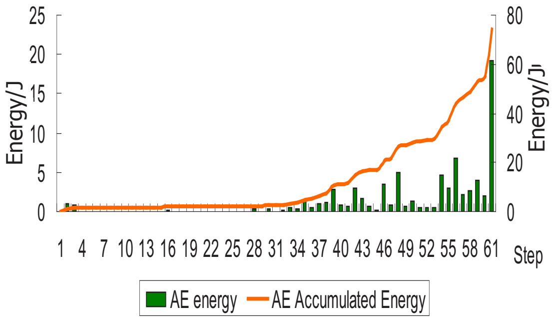


Fig.6. AE energy with load step

Combined with the process of AE diagram, it could be concluded from AE Energy diagram and AE Accumulated Energy diagram that the process of hydraulic fracturing had five stages:

(1) Stress accumulation stage (1-14MPa). At this stage, high pressure water mainly entered into original coal fracture in the form of seepage. Along with the water pressure increasing, the water seeped into microfractures. Free gas in the microfractures was compressed and gas pressure increased. Gas pressure was the main obstacle of water seeping into coal seam at this stage, only a little AE, as shown in figure 4 (a). The AE energy and AE accumulated energy also were little, as shown in figure 5 and figure 6 (1-26 steps). This phase gradually formed a pressure increasing circular around the hole, and principal stress around the hole radiated out in distribution.

(2) The crack stable extension stage (14-18MPa)

When the pressure in the hydraulic fracturing hole loaded up to 26 step, namely the pressure was 14 MPa, many scattered micro cracks emerged around with pressure increasing circular which was near the hole, as shown in figure 4 (b). Micro cracks caused by the damage of weak plane, because of the coal rock medium was inhomogeneous, weak plane was random distribution and the micro fracture generated random. The AE accumulated and AE accumulated energy increased gradually, as shown in figure 5 and figure 6(26-34step).

(3) Forming local destruction zone stage

Microcrack not communicate with main crevasse appeared near the main cracks apex by the increasing of the hole pressure, and these microcracks were increasing. The main cracks expanded faster, and water pressure relayed along the pore, as shown in figure 4(c) below. AE accumulated counts and AE accumulated energy had greater development, as shown in figure 5 curre of acoustic emission times and figure 6 the curre of acoustic emission energy, whose slope were great increase (34-46step). The main crevasses develop fast in this stage.

(4) Local damage expansion and breakthrough stage (24-29MPa)

When the pressure in the hydraulic fracturing hole loaded up to 46-56 step, namely the pressure was 29 MPa, the development speed of the main fracture and nearby microcrack accelerated and the development process became complicated. Some sporadic microcrack connected to main fracture gradually, and influence radius of pressure was up to 6 m, as shown in figure 4 (d) and figure 4 (e). AE speed slightly slowed down in this stage, as shown in figure 5 and figure 6 (46- 56step), having a slightly lower slop than the (3) stage had. The main fracture developed slowly, but secondary fracture and transfixion crack expanded faster.

(5) Fracture instability and extension stage (29-31MPa)

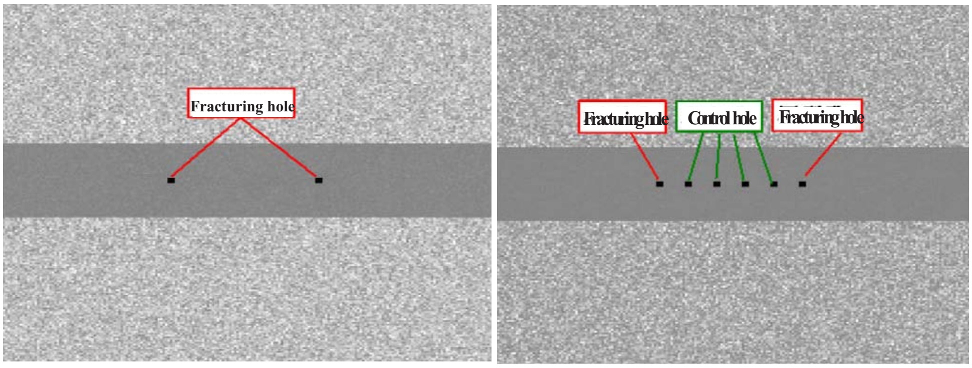
Fracture still continued to expand without extra pressure. When the pressure in the hydraulic fracturing hole loaded up to 60 step (31 MPa), acoustic emission had a large sudden jump, and fracturing became instable. The acoustic emission increased showed that fracture extension speed accelerated. At this time, the tip of the main fracture sprouted many irregular cracks, which bifurcate obviously, the number and scale of cracks greatly increased. Under the effect of secondary fracture, the main fracture extension path became more tortuous. When the crack developed to a certain extent, the expansion would end. To make fracture extension happen again，higher water injection pressure was needed. At this time, the fracturing radius reaches 7-8 m, as shown in figure 4 (f).

3.3. Directional Hydraulic Fracturing Process Failure Analysis

Using contact viewpoint to research double holes fracturing problems, setting the two fracturing holes 15m apart to simulation, the extension of fracturing crack situation was investigated when there were directional holes and no directional holes. The plane models are shown in figure 7.

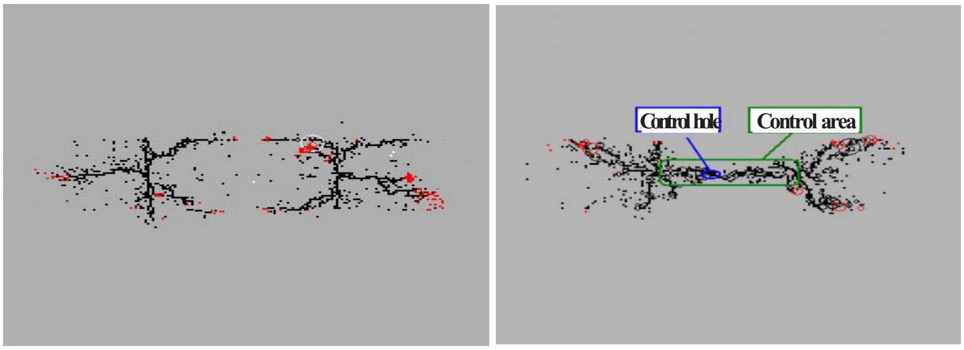
Contrast figure 8 (a) and figure 8 (b), it was evident that hydraulic fracturing with directional holes produces more fracture than without directional holes. And because of directional holes, there were many fractures linking up radial fracture around the directional holes along the line direction connecting fracturing hole and directional holes.

Because directional hole has weak face, fracture expansion in this direction required less pressure than in the other directions. Under same pressure, fracture development and expansion gave priority to this direction. That is to say, two drillings hydraulic fracturing created a cylindrical compression crushing circle around the fracturing hole inside coal or rock mass and a throughout fracturing area along the line direction connecting fracturing hole and directional holes.



(a) No control hole (b) Control holes existing

Fig.7. Calculation modeling of hydraulic fracturing



(a) No control hole (b) Control holes existing

Fig.8. AE Diagram of two drillings after hydraulic fracturing

3.4. Determining the Distance of Directional Holes and Fracturing Holes

In order to reasonably determine distance between fracturing hole and directional hole, achieving fully relief and expanding the effective area of fracturing as possible, under the condition of single fracturing hole, the distance between fracturing hole and directional hole was respectively set 2m, 3m, 4m, and the pressure was set 27 MPa, then simulation was performed as shown in figure 7(b). Pressure change of a point in different distance was shown in figure 10 (a) to figure 10 (c).

Comparing above pressure figures, it can be seen that, pressure in figure 10 (c) are positive (in RFPA2D-Flow system, positive value is compressive stress, and negative value is tensile stress), unit points in this place is not affected by tensile stress. So this time, the distance between directional hole and fracturing hole should be decreased in correspondence.

When the distance between directional hole and fracturing hole is 3m, unit points nearby directional hole is also affected by tensile stress producing cracking damage, but discharging pressure degree is lower than 2 m distance.

Through comparative analysis on pressure change of unit point close to directional drilling in different distance and combining engineering economic principles, the distance between directional hole and fracturing hole would be 3 - 4 m. 3 m was taken for safety.

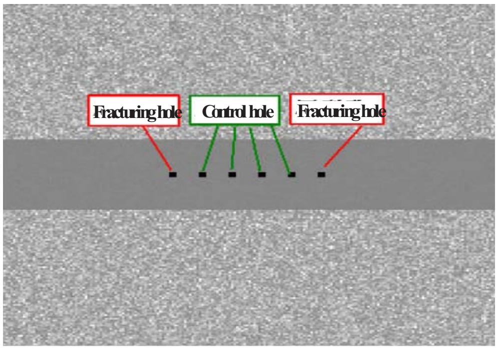
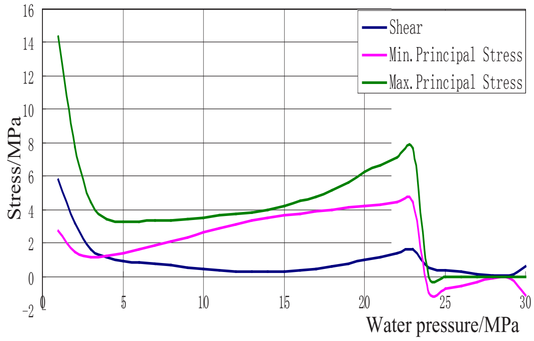
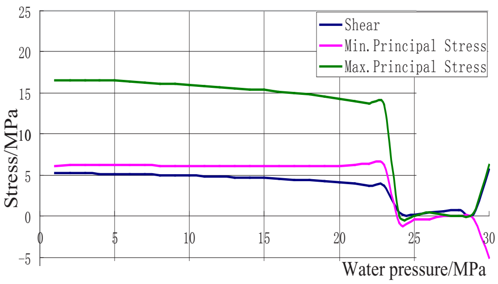


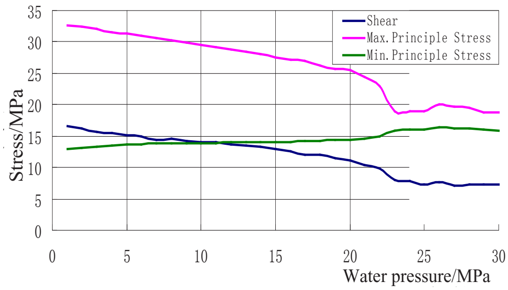
Fig.9. 2m spacing between directional drilling and fracturing drilling



(a) The stress variation of unit point close to directional hole which was 2m from fracturing hole



(b) The stress variation of unit point close to directional hole which was 3m from fracturing hole



(c) The stress variation of unit point close to directional hole which was 4m from fracturing hole

Fig.10. Stress change of unit point close to directional drilling in different distance

4. Field application and effect

4.1. Site construction layout

Directional hydraulic fracturing technique was applied in the F_{15}-31010 mining workface of The Twelfth Coal of Pingdingshan Coal Mining Group. The site construction layout was shown in figure 11.Down hole was designed in F_{14} coal seam ventilation passage, through the top of F_{15}-31010 ventilation passage to the bottom of F_{16}/F_{17} coal seam, and crossing-layers directional hydraulic fracturing was implemented. After directional fracturing, pressure relief area was formed between F_{14} ventilation passage and F_{15} ventilating roadway, playing a role of discharging pressure protection to lower part of F_{15} coal seam roadway. The position of directional hydraulic fracturing hole should be 60m ahead of the heading face .Considering the quality and safety of hole sealing, the highest pressure was set 27 MPa

4.2. Effect of application

(1) Fracturing influence range

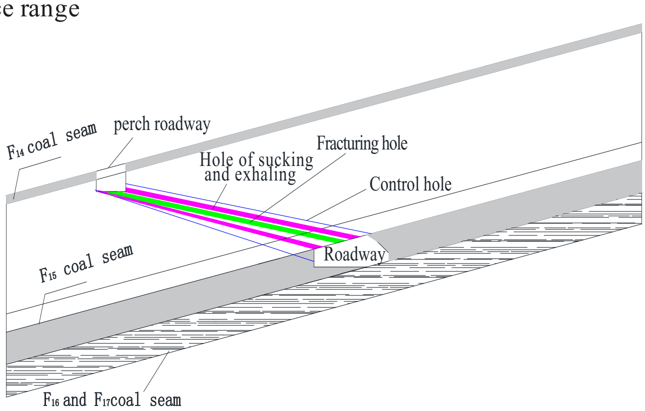


Fig.11. The cross-section of deep crossing-hole directional hydraulic fracturing in 31010 roadways

Investigation drilling was laid on one side of the fracturing hole, paralleling to the fracturing drilling. There is an investigation hole every 1m, and the total number of investigation drilling is 10, whose aperture is 42 mm. Gas drainage concentration for the first 15 days was analyzed. The result is shown in figure 12.

It can be seen from the figure that gas concentration increases obviously after hydraulic fracturing and the influence range of hydraulic fracturing is approximately 6-7m. The measurement of influence radius and the results of the numerical test are consistent.

(2)The comparison of directional hydraulic fracturing and no-directional hydraulic fracturing

The experiment was divided into two groups. There were 5 directional hydraulic fracturing holes in the first group, 5m apart each other, and there were 5 no-directional hydraulic fracturing holes in the second group, 5m apart each other too. The concentration and flow of each drilling drill-hole were recorded in 20 days. The dates of each group were in average, obtaining the daily flow and concentration of directional hydraulic fracturing and no-directional hydraulic fracturing. A variation of flow was figured, as shown in figure 13.

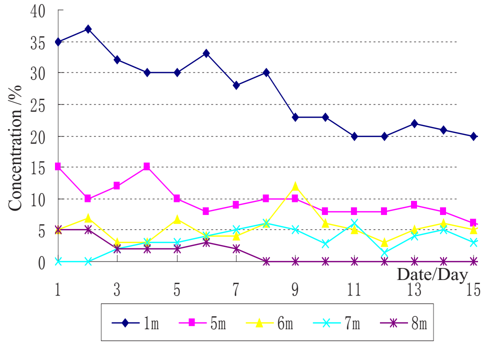


Fig.12. The changes of gas concentration after hydraulic fracturing

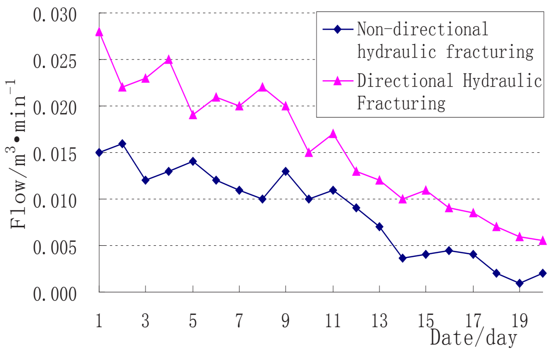


Fig.13. Drainage flow before and after fracturing

The concentration of no-directional hydraulic fracturing is 8% and the flow is 5.9×10^{-3} m^3/min, which reduce to 0.01 m^3 / min after 10 days. And directional hydraulic fracturing concentration grows up to 15%, the maximum flow up to 27.8×10^{-3} m^3/min, daily average up to 16×10^{-3} m^3/min, and drainage concentration become stable. The average drainage concentration promotes 87.5%, average flow up 55.6%.

5. Conclusions

1) The mechanism of hydraulic fracturing is analyzed, the directional hydraulic fracturing technique is proposed, and the mechanism of directional hydraulic fracturing is discussed.

2) Through the simulation of RFPA2D-Flow software, the fracturing process of crack starting, extending and elongating are reappeared. The characteristics of the process are analyzed, and the fracture distribution laws of directional hydraulic fracturing and no-directional hydraulic fracturing are revealed. The simulation in the F_{15}-31010 mining workface of The Twelfth Coal of Pingdingshan Coal Mining Group shows that single-drillhole fracturing effective radius reaches up to 6m under the pressure of 27Mpa

3) After fracturing, the average drainage concentration promote 80%,average flow up 382%.all this suggest that this technique can induce fracture extension and development, expand the range of hydrofracture and improve the gas drainage efficiency effectively.

Acknowledgements

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