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ORIGINAL PAPER

Research on Application of Hydraulic Fracturing Enhanced Technology in Coal Mine

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Abstract Coal and gas outburst accident is one of the critical disasters restricting the safety production of coal enterprises in China. To solve the problems of low permeability and difficulty in gas extraction, a hydraulic fracturing test was carried out according to the occurrence characteristics of coal and rock gas in Pingdingshan Coal Mine No. 12; and the change law of the gas concentration and flow rate after hydraulic fracturing were obtained through long-term monitoring. Based on the test results, the effect of hydraulic fracturing on gas permeability enhancement of coal and rock was analyzed. The results have shown that the gas content decreases obviously and yet the water content increases since the hydraulic fracturing test completed, which makes the effect of gas displacement remarkably. It not only provides a reference for implementing hydraulic permeability enhancement and enhanced extraction in deep high outburst mines but also provides safe and efficient production in mining.

Keywords Hydraulic fracturing · Pressure relief and permeability enhancement · Water content · Gas extraction · Outburst coal seam

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1 Introduction

Coal/gas outburst is a strong dynamic process in underground gas-bearing coal and rock mass which moves rapidly from coal seam to mining site in the form of crushing and pulverizing accompanied by a large amount of gas emission; it would seriously threaten the safety of Coal Mine production (Yan et al. 2013). The main factor restricting the further improvement of CBM extraction scale in China's are raw coal, extraction rate, and per-ton extraction volume while increasing extraction rate is the only way to increase extraction scale (Yuan et al. 2013). However, the low permeability and heterogeneity make it difficult to extract gas effectively by conventional methods. Hydraulic technology is an effective way to increase coal permeability (Wang et al. 2014).

In recent years, domestic and foreign researchers had studied the variables related to hydraulic fracturing test which had a certain reference function for the specific field work. Taleghani et al. (2016) and Taheri-Shakib et al. (2016) found that the existence of such natural fracture would lead to deviation of hydraulic fracturing due to the change of stress state around it and the increase of stress in hydraulic fracture. Liu et al. (2014) used triaxial fracturing system simulating the influence of natural fracture network found the principle of hydraulic fracture propagation follows the principles of minimum resistance, best propagation, and shortest propagation path. Moradi et al. (2017) adopted the higher-order displacement discontinuity method to studying the crack opening displacement (cod) behavior of HF (i.e. the width of HF) under different conditions, it was shown that the spacing and angle of intersection have a significant influence on HFS propagation. Zhou et al. (2019) simulated water injection process under the actual mining conditions to study the influence of complex fissures on the impact of water injection in low-pressure coal seam and the monitoring data showed that water injection in low-pressure coal seam in dynamic mining pressure area can achieve better effect of anti-scouring and dust suppression. Meanwhile, Pathak and Ramana (2019) determined in situ stress through hydraulic fracturing technique (HFT) on three HFT parameters: shut-in pressure, reopening pressure and fracture direction, the uncertainty of HFT parameters must be considered in the design process to avoid unreasonable engineering judgement. He et al. (2017) found that conventional hydraulic fracturing was uncontrollable and determined by the direction of minimum in situ stress. Wang et al. (2019) studied the influence of injection rate on hydraulic fracturing effect by preparing the artificial interlayer model block through the laboratory-scale test, which had shown that hydraulic fracturing effectiveness improved with the increase of injection rate. Zhang et al. (2019) conducted a field experiment and combined with numerical simulation analysis to estimate the influence range of hydraulic fracturing, it turned out the plastic zone principally distributes along the interface of the coal seam and roof due to the existence of stratification.

The main mining face of the third level West Wing of Pingmei No. 12 Coal Mine has 1000 m in buried depth. Hitherto, the technical route of gas control in regional coal seam is adopted by low-level drilling. The coal reservoir is affected by high geo-stress and low permeability. At the same time, the gas content is high as well as extraction difficulty, the gas control work has become a difficult problem urgent to solve. According to the occurrence characteristics of coal and gas in 31040 working face in Pingmei Coal Mine No. 12, we had designed an industrial test scheme of hydraulic fracturing, made a long-term investigation and analyzed the test results; also, formed an integrated extraction technology of "drilling-sealing-fracturing-cut-off extraction" in low rock roadway, which would increase the hydraulic efficiency for deep high-inrush mines. It could be used for a reference to realize safe and efficient mine production through hydraulic fracturing strengthening extraction as well.

2 Survey of Experimental Area

The Coal Mine No. 12 was originally located in the eastern part of Pingdingshan Mine, which built in 1958 with an approved production capacity of 1.3 million tons per year. The northern third level lied in the transition area of eastern elevation end in Likou syncline axis which belonged to the stress concentration zone, so the middle and small faults were well developed; the minefield was a monoclinic structure inclined to the north–north-east as a whole belonged to the structurally complex area in Pingdingshan mining (Gao et al. 2014; Zhang et al. 2013). The main coal Ji_{15}, $Ji_{16\text{-}17}$ were fat coal, primary coking coal, and one-third coking coal. Coal dust was explosive with the 31.77% explosion index and 10 mm flame length, and the spontaneous combustion grade was second in a 2–8 months period. The absolute gas emission rate was 50.39 m^3/min, relative gas emission rate was 20.16 m^3/t, besides the permeability coefficient was 0.0141–0.0218 m^2/MPa^2 d which belonged to the difficult drainage coal seam. Working face $Ji_{15\text{-}31040}$ was located in the upper part of the three levels west wing. It was adjacent to the protective coal pillar of the industrial square in the east, the mine field boundary in the west, the working face $Ji_{15\text{-}31020}$ in the south and the unmined area in the north. The working face length was 1100 m and the strike length was 240 m. The working **face elevation ranged from − 699 m to − 714 m, the ground elevation was from 345 m to 365 m and the vertical depth was from 1044 m to 1059 m. The coal thickness of working face Ji_{15} was 3.3 m with an average dip angle of 10 degrees, gas pressure of 1.30 MPa and gas content of 12.86 m^3/t. $Ji_{16\text{-}17}$ coal was 0–1.8 m thick with the interlayer distance of 5.4 m, gas pressure of 1.06Mpa, gas content of 11.84 m^3/t, and average interval between coal seams of 11 m; also the consistent coefficient was 0.2–0.5 and the failure type was II to III. Because there were several shortcomings in this area, to be specific: deep carving, high gas content, bad permeability, difficult to extraction, and long treatment cycle; besides the gas control was hard during mine excavation which had a serious effect on replacing the "drainage-excavation-mining" as the safe production.

3 Technical Scheme of Hydraulic Fracturing Test

3.1 Drilling Design

Six hydraulic fracturing boreholes were arranged in $Ji_{15\text{-}31040}$ haulage roadway/low-located drainage roadway, and hydraulic fracturing was carried out in the working face of the belt roadway. We had predicted 35 m influence radius, 50 m borehole spacing and 94 mm diameter; avoided the fault geological structure concurrently; also, made sure that the vertical distance between the final FR borehole and the fault intersection was more than 20 m, and the final drilling hole was about 0.5 m away from the roof, and did not penetrate coal seam. After fracturing was done, 4 pressure boreholes and 18 effect observation holes were constructed around each fracturing hole to determine the gas parameters. The pressure boreholes were used to determine the changes of gas pressure, flow attenuation coefficient and gas permeability coefficient; and the effect testing boreholes were used to measure parameter variations of gas content, water content and CBM operating flow; along with the fracturing effective range which was showed in Fig. 1. At the same time, the pre-drainage boreholes were constructed 25 m at the top and 25 m at the bottom in the outline of $Ji_{15\text{-}31040}$ belt roadway. On one hand, it would prevent gas from refluxing; on the other hand, it would drain the expelled gas in the fracturing process in time. At the construction site, 84 rows are constructed 9 m inside towards the opening of $Ji_{15\text{-}31040}$ belt roadway/low-located drainage roadway, with 2 in each row and 6 m row spacing. The hole was sealed according to the standard and extraction parameters were tested simultaneously.

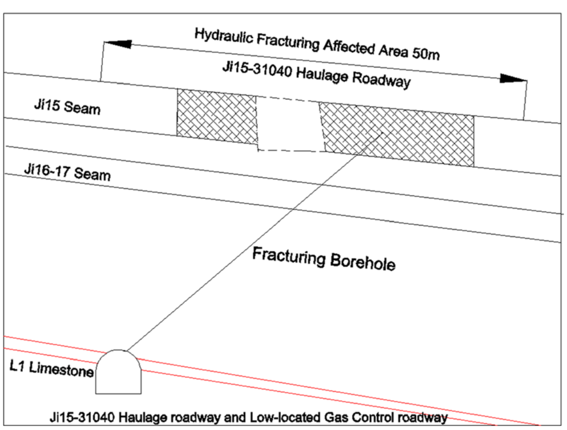

Fig. 1 Schematic diagram of hydraulic fracturing and investigation borehole design

3.2 Sealing Technique

The fracturing borehole sealing technique adopted the multiple sealings method with cement paste through full-holes process. The sealing material used ordinary cement and expansive agent U. According to the theoretical analysis, the minimum sealing length of fracturing pipe was 15.4 m. The pre-selected fracturing location satisfied the minimum sealing length requirements and the fracturing feasibility.

The fracturing pipe was dropped to end borehole and ensured that screen pipe section was 1 m higher than the bottom, also the return slurry pipe was 0.5 m higher than the bottom; meanwhile, a 6 m long grouting pipe was placed at the ostiole. The cement paste (water: cement: expansive agent = 1:2:0.2) was continuously injected through the grouting pipe by the mud pump when the reverting slurry was successfully; then the first grouting was completed and firmly grouted. The slurry pipe was injected with clean water into the return slurry pipe, cleaned grouting pipe and fractured pipe for 5–10 min, meanwhile, kept the return slurry pipe open. After 16 h solidification, the return slurry pipe was grouted and ended when the fracturing pipe was reverting slurry; then the return slurry pipe closed and the sealing operation was accomplished. After another 48 h solidification, the fracturing test could be carried out. As was shown in Fig. 2.

3.3 Hydraulic Fracturing Test Scheme

During the construction of all drilling boreholes, hydraulic powder drainage was used in the rock section. After the coal showed out, it used air pressure to drain instead. The gas content, initial moisture, and

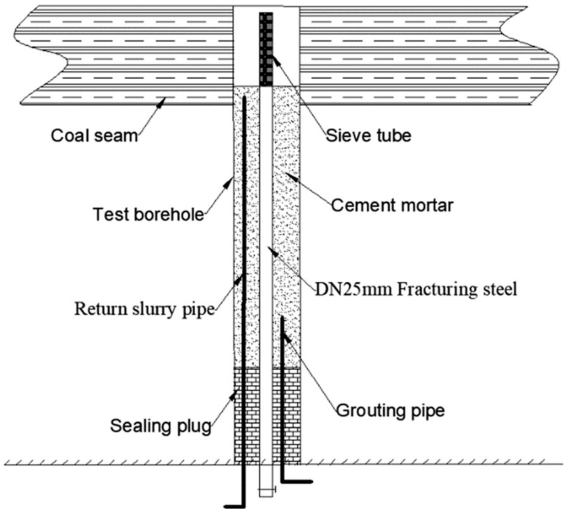

Fig. 2 Schematic chart of fracture hole sealing

occurrence (whether the gangue or soft stratification existed or not) were determined by Ji_{15} coal sample. When the 1#–6# boreholes of hydraulic fracturing drilling were completed, sealing the holes with DN25 mm fracturing steel immediately. The fracturing mode and method were through-layer drilling fracture and multiple times cyclic fracturing techniques. The single hole was circulated for 3–5 times in turn and maintained pressure for 2 weeks after fracturing. When the fracturing completed, the water and pressure had been released along with boreholes been sealed. After all this, the drainage was taken into action. At the same time, in order to ensure that the fracturing water could be successfully pressed into the target seam, the injection quantity and pressure was not lost; the pre-geological drilling holes, core drilling holes and gas release holes that had been constructed in $Ji_{15\text{-}31040}$ belt roadway and low-located gas control roadway needed to be sealed with cement paste.

The BYW450/70 underground fracturing pump group produced by China Coal Technology Engineering Group Chongqing Research Institute was used during the fracturing test. The rated pressure of the fracturing pump should be greater than the pump injection pressure Pw and at least its power was the product of the pump injection pressure and flow rate. Based on the preliminary calculation, the initiation pressure of Ji_{15} coal in Pingdingshan Coal Mine No. 12 was about 20–25 MPa, and the pumping pressure was about 25–30 MPa. For some coal seam, the amount of fracturing fluid was related to the coal seam physical properties. According to the calculation, the water injection volume of the fracturing hole was about 100 m^3. The water injection volume would be adjusted according to the actual situation at any time. If the roof or roadways surrounding the fracturing boreholes were fractured, the water injection volume would be reduced appropriately. Fracturing water supply required the clean water, filtered out impurities with 2 mm diameter or more, the water pressure should be greater than or equal to 2 MPa and the water flow rate was 20 m^3/h. Fracturing high-pressure rubber hose adopted customized high-pressure rubber hose with a nominal inner diameter of 51 mm and length of 20 m. Its pressure-bearing capacity was not under the requirement of F grade in GB/T 241445-2009 specification for rubber hose and hose assemblies for rotary drilling and vibration reduction. (verification pressure:103.4 MPa, minimum burst pressure:155.3 MPa); and joint form was Ren joint (one male connector, one female connector, rated pressure:105 MPa, nominal pipe diameter:2inch). After all fittings had been debugged and installed, opened the fracturing pump group and closed the decompression valve slowly until it had reached the setting pressure. After 5 min without abnormality, ended fracturing and got into the pressure-retaining segment. The test parameters of each holes were shown in Table 1.

In the fracturing process of the six holes, no sign or phenomenon was found about any deformation of roof. The 1# borehole had the longest holding time and the initial holding pressure was 23 MPa. Two weeks later, the opening holding pressure of 1# borehole was 8 MPa; however, the holding pressure of the 2# borehole,3# borehole,4# borehole,5# borehole all decreased to 0 MPa. During the fracturing process of 2# borehole and 3# borehole, the water leakage in the roof was seriously and slowed down gradually when several rain curtains were formed. Yet in other fracturing boreholes, there was no obvious water leakage and the roof integrity was quite good.

4 Effect Analysis of Hydraulic Fracturing Test

4.1 Situation Analysis of Gas Extraction

Through statistical measurement of gas extraction parameters, the gas concentration variations by

Table 1 Summary of hydraulic fracturing test parameters

Number	Injection pressure (MPa)	Fracturing times	Holding pressure (MPa)	Downward holding pressure (2 weeks later) (MPa)	Cumulative injection (m^3)
1#	22–28	5	23	8	110.25
2#	18–22	5	11	0	115.86
3#	13–18	4	14	0	106.76
4#	11–20	4	17	0	110.25
5#	20–22	3	22	0	106.67
6#	16–22	5	8	8	196.27

hydraulic punching in $Ji_{15\text{-}31040}$ belt roadway/low-located drainage roadway and adjacent working face had been analyzed, as shown in Fig. 3. Statistical analysis was made about the gas concentration variations and flow rate which changed over time in the drainage system of $Ji_{15\text{-}31040}$ belt roadway/low-located drainage roadway. The total amount of gas drainage was 613,000 m^3 for 157 days. At present, the system concentration was 59% and the extraction purity was 5 m^3/min, as shown in Fig. 4.

According to Fig. 3, the average initial concentration of boreholes constructed in the hydraulic fracturing experimental area was 60–70%; after 150 days pre-drainage was exceeded 60%. The average initial gas concentration of hydraulic punching in $Ji_{15\text{-}31040}$ belt roadway/low-located drainage roadway and adjacent working face ranged from 20% to 30% and after 90 days pre-drainage reduced to less than 10%. Under the same "two blockages and one injection" pressure sealing technique, the gas concentration in hydraulic fracturing experimental area increased by 1.8 times and the effective pre-drainage time increased over 150 days. Gas flow rate was 2–5 m^3/min. According to Fig. 4, after gradually implemented the hydraulic fracturing test, the gas concentration in the test area ranged from 30% to 65% and pure gas flow was 2–5 m^3/min.

The gas reserves should be the length of treatment 300 m * width of treatment 55 m * coal thickness (5.1 m = Ji15 thickness 3.3 m + Ji16, Ji17 thickness 1.8 m) * specific gravity (1.31) * gas content (12.86 m^3/t), which turned out to be 1417600 m^3. The residual gas content was 7.3 m^3/t and the pre-drainage rate was 43.2%. According to the data, the residual gas content could be reduced to less than 6 m^3/t after 176 days (5.9 months) pre-drainage when the hydraulic fracturing completed. The total length of $Ji_{15\text{-}17}$ coal section was 736 m, the drainage volume of 100-meter borehole increased from 0.02 m^3/min.hm to 0.68 m^3/min.hm which raised to 34 times.

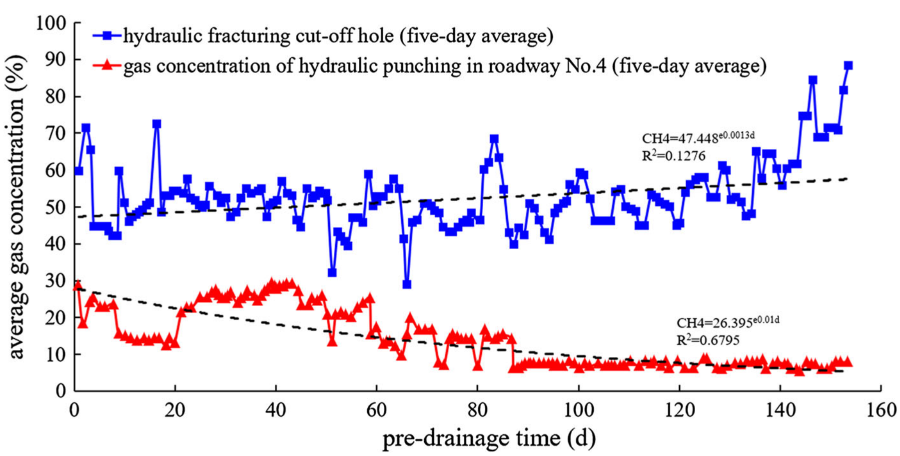

Fig. 3 Gas concentration changes in closuring pre-drainage borehole of hydraulic fracturing experiment

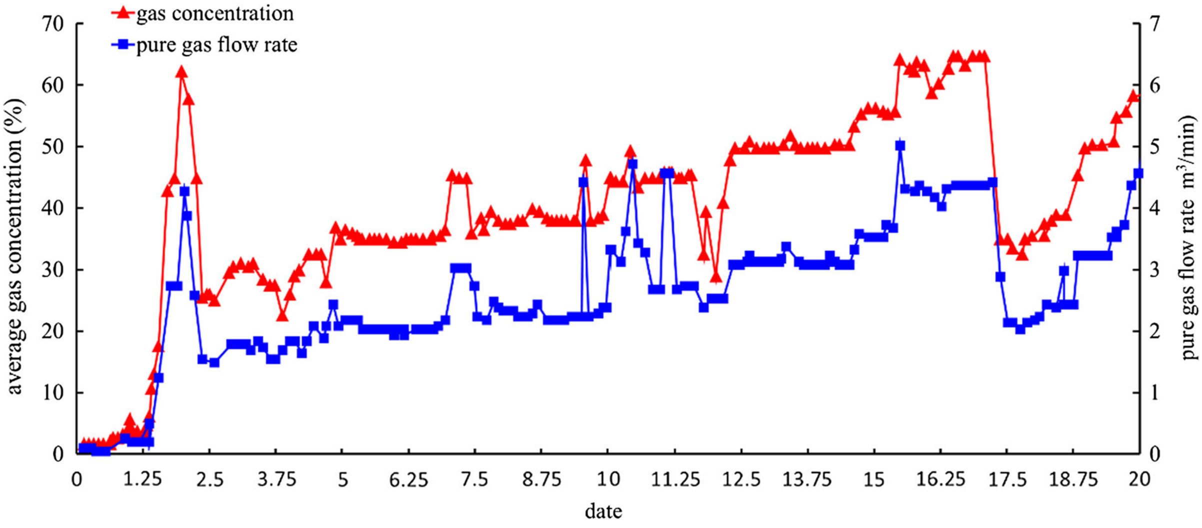

Fig. 4 $Ji_{15\text{-}31040}$ gas parameters variation in Pipeline of haulage roadway and low-level control roadway drainage system

It can be found that after hydraulic fracturing, the permeability had been improved substantially as well as the drainage concentration and purity. The reason was that with high pressure water had injected into the fractured hole from the angle direction, abundant cracks were formed around each hole which would increase the permeability of coal seam.

4.2 Effect Analysis of Gas Extraction

According to the data measured before fracturing, the original gas content of Ji_{15} coal seam in this area was 5.41–12.86 m^3/t with an average of 8.60 m^3/t. After fracturing, a total of 18 observation boreholes had been taken samples and determined the gas content, as shown in Fig. 5. There were 9 boreholes along strike where with 28 m from 1#borehole and the measured gas content was 2.88–7.36 m^3/t, which was about 4 m^3/t lower than the original average. Also, there were 9 boreholes along incline where with 35 m from 1#borehole and the measured gas content was 2.27–3.36 m^3/t, which was about 4.5 m^3/t lower than the original average. Among that, the gas content of 17 boreholes was below 6 m^3/t and the range of gas content discount along the incline was more than that along the strike.

The original gas content of $Ji_{16\text{-}17}$ in the test area was 9.63–13.84 m^3/t with an average of 10.70 m^3/t. After fracturing, the gas content was measured by 18 inspection boreholes, as shown in Fig. 6. There were 9 boreholes along strike where with 28 m from 1# and the measured gas content was 5.57–9.92 m^3/t, which was about 2 m^3/t lower than the original average.

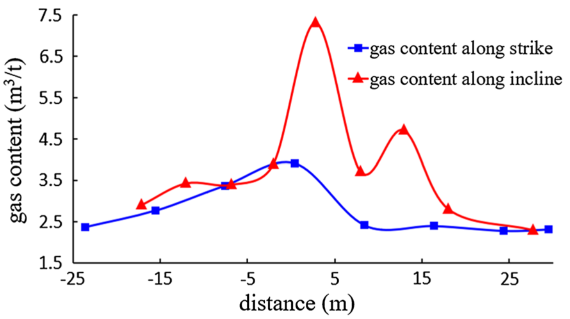

Fig. 5 Ji_{15} scatter diagram of gas content change post-fracturing

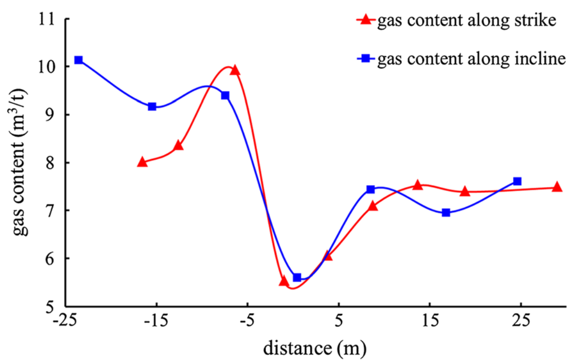

Fig. 6 $Ji_{16\text{-}17}$ scatter diagram of gas content change post-fracturing

Also, there were 9 boreholes along incline where with 35 m from 1# and the measured gas content was 6.38–10.11 m^3/t, which was about 1.5 m^3/t lower than the original average. The decrease of gas content in the outer section along the strike was larger than that in the inner section, and the range of gas content discount in the lower section along the incline was more than that in the upper section.

The gas pressure of Ji_{15} in test area was 0.83–1.3 MPa and $Ji_{16\text{-}17}$ was 0.86–1.06 MPa. After fracturing, gas pressure was measured at two (P1, P2) and four (P1-1, P1-2, P1-3, P1-4) boreholes of $Ji_{16\text{-}17}$ constructed area including in $Ji_{15\text{-}31040}$ low gas control roadway; and statistical analyzed gas pressure after fracturing as well. The gas pressure of P1# in Ji_{15} displayed as 1.2 MPa and that of P2# displayed as 1.5 MPa. When the pressure gauge of P2# was disassembled along with running water; otherwise, the pressure gauge of P1# was disassembled with 800 mL water pumped out. Through correction calculation, the gas pressure of P1# was 1.07 MPa. The gas pressure gauge of $Ji_{16\text{-}17}$ appeared that P1-1# was 0.48 MPa, hole P1-2# was 0.35 MPa, hole P1-3# was 0.8 MPa and hole P1-4# was 2.32 MPa. Among that, P1-2# was not tightly sealed, P1-4# disassembly pressure gauge was along with flowing water and P1-3# disassembled pressure gauge with draining 1200 mL water; through correction calculation, gas pressure of P1-3# was 0.71 MPa. Therefore, the gas pressures of Ji_{15} and $Ji_{16\text{-}17}$ after fracturing were 1.07 MPa and 0.71 MPa and decreased by 0.22 MPa and 0.35 MPa respectively.

It had shown that during the fracturing process, the permeability had been increased because of the coal seam damage/destruction; consequently, the closer the fracturing hole got, the clearer damage to coal seam would be. Therefore, the gas drainage volume in the fracturing holes area and their adjacent was higher than others, which verified the displacement effect of high-pressure water on gas during fracturing process.

4.3 Analysis of Water Content Variation

According to the data measured before fracturing, the original water content of Ji_{15} in the area was 1.25–1.28% which changed lightly and the average change rate was 1.26%. After fracturing, all 18 observation boreholes were constructed to measure the water content of the coal seam, as shown in Fig. 7.

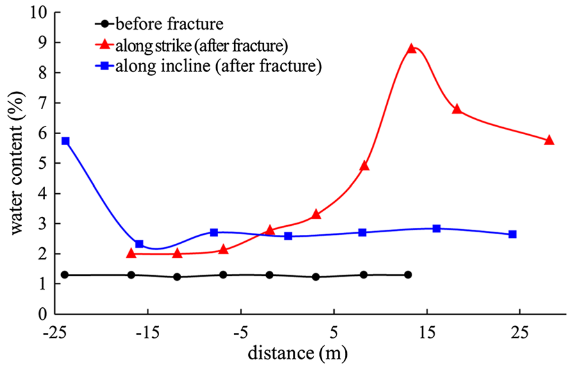

Fig. 7 Ji_{15} contrast curve of water content change before and after fracturing

There were 9 boreholes along the strike where with 28 m from 1#borehole, the measured water content was 1.93–8.74% which was about 5 times more than the original average. Moreover, the increase of water content in the outer was larger than that in the inner. Also, there were 9 boreholes along incline where with 35 m from 1#, the measured water content was 2.36–5.79% which was about 3 times more than the original average. The water content was risen faster along the strike than that along the incline.

And the original water content of $Ji_{16\text{-}17}$ was 1.03–1.11% which changed lightly and the average change rate was 1.05%. After fracturing, all 18 observation holes were constructed to measure the water content of coal seam, as shown in Fig. 8. There were 9 boreholes along strike where with 28 m from 1#, the measured water content was 1.53–16.74% which was about 8 times more than the original average. Moreover, the increase of water content in the outer was larger than that in the inner. Also, there were

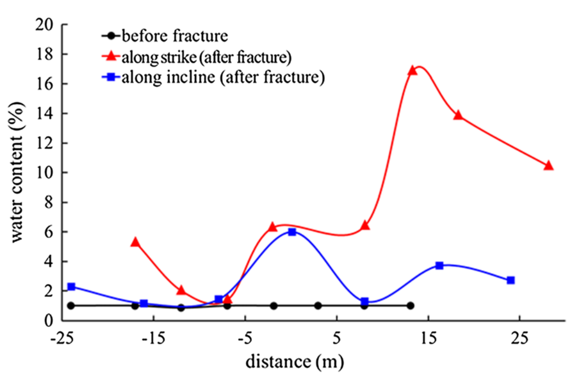

Fig. 8 $Ji_{16\text{-}17}$ contrast curve of water content change before and after fracturing

9 boreholes along the incline where with 35 m from 1#borehole, the measured water content was 1.42–6.15% which was about 2 times more than the original average. The water content was risen faster along the strike than that along the incline.

Water in coal reservoir reduced the CBM (coal bed methane) throat during migration, as well as the CBM relative effective porosity decreased in this layer; it would lead to the decrease of effective permeability. Therefore, when the lower the water content was, the higher the relative effective porosity was during CBM transported and the higher the effective permeability was in coal reservoir as well.

5 Conclusion

Based on the analysis, the gas content and pressure of Ji_{15}, $Ji_{16\text{-}17}$ decreased obviously; the water content was apparently increased and the effect of fracturing on gas displacement was remarkable after hydraulic fracture. The effective range of fracturing reached more than 35 m. Some conclusions are drawn as followings:

(1) Through the optimization of drilling parameters with the application of techniques such as: "two blockages and one injection" sealing method, implementation of hydraulic fracturing and combined pipeline enhanced drainage layout technology. As a consequence, the gas emission volume and concentration in drilling holes were greatly increased and its extraction efficiency also improved, which reduced the time of draining, improved outburst elimination effect in working face and shortened the "pumping-digging-mining" continuous time

(2) With the implementation of hydraulic fracture, the original small fractures of coal reservoir were fully expanded, stretched, connected, and produced the secondary fractures. Under 19.2 MPa of water pressure: (1) the effective influence of single-hole fracturing ranged from 11 m to 12 m; (2) the permeability coefficient of coal seam was increased by 13.43times; (3) the attenuation coefficient of borehole flow was reduced by about 2 times. After pumped about 11 months, the gas content in coal seam decreased from 4.83 to 2.35 m^3/t which greatly released the gas in coal seam. At the same time, it increased the water content, softened the coal body, greatly reduced dust production and weakened the risk of coal dust explosion.

(3) After the application of hydraulic fracturing measures, the average concentration drainage increased by 40% and the volume of 100-meter borehole advanced 34times for each one. Finally, the transformation from high to low gas face was realized which provided a strong guarantee for safe and efficient working face.

In this paper, we just chose gas extraction and water content as evaluation indexes when analyzed the gas governing effect by hydraulic fracturing technology; economic benefit, cost control, energy consumption control and other evaluation indexes need to be further studied.

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