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Coal Bed Methane (CBM) Stimulation by Liquid CO_2 Phase-transition Fracturing (LCPF) Technology

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Abstract: The permeability of coal seam is the main factor restricting the safe production of coal bed methane (CBM). In order to improve the extraction efficiency of CBM and reduce the probability of coal and gas outburst, it is of great significance to adopt artificial measures to enhance the connectivity of fracture network of coal reservoir. In this paper, the modification test of the fracture network in soft and low permeability coal seam is carried out by using the liquid CO_2 phase-transition fracturing (LCPF) technology through cross-boreholes in bottom drainage roadway. The results showed that the diameter of the borehole is obviously increased, and the gas flow rate and gas concentration are greatly enhanced, which indicates that the pores and fractures of the coal reservoir are effectively connected, and the influence radius of gas extraction is about 10m. Although, at the later stage of gas drainage period, the pure gas quantity and gas concentration show a decay trend, they still maintained at a high level, which is favorable for CBM extraction. Compared with hydraulic fracturing, the LCPF technology has better effect on permeability enhancement of coal seam in the early drainage stage after fracturing. The LCPF technology not only enhance the CBM extraction efficiency, but also shorten the driving period of roadways.

Keywords: Cross-boreholes, Liquid CO_2 Phase-transition Fracturing, Influence Radius, Extraction Efficiency, Pure Gas Quantity, Gas Concentration

1. Introduction

As we all known, the major fossil energy sources in the world are coal, oil and natural gas, while China's energy structure is characterized by "rich coal, poor oil and little gas". Although China has actively developed new energy sources at the present stage, the foundation of new energy industry is still weak and the cost of technology is high, so it will take time for large-scale utilization. In brief, it cannot be changed that coal will be the engine of China's economy for a long time.

Underground mining method has been widely adopted in Chinese coal mines. Due to the high-intensity mining, the shallow coal resources have been exhausted, and deep mining is an inexorable trend to the development of coal industry. The depth of mineral deposits increases every year, which inevitably leads to the deterioration of mining conditions. Among them, the gas power disaster (gas explosion, coal and gas outburst, etc.) is the most serious, which has become the main disaster restricting the safety production. Therefore, domestic and foreign experts have proposed many effective methods to improve the permeability of coal seam.

In order to improve the efficiency of gas extraction, domestic and foreign experts devote themselves to reforming the fracture network of the original coal reservoir with different methods, including deep-hole pre-splitting blasting [1-2], hydraulic slotting [3-5], hydraulic fracturing [6-9] and gas fracturing technology [10-11], etc. so as to improve the permeability of coal seam. However, different methods are applicable to different coal seam conditions. In the process of hydraulic fracturing, a great number of water (or other fluid, or mixed with proppants, such as sand, glass beads, etc.) with high pressure provided by the pump is injected through a cross-borehole or in-seam borehole into coal seam to create fracture network composed of vertical and parallel fracturing, which has a scope of fracturing 55-57m [12-13]. In a hydraulic slotting operation, the ultra-high pressure pump pressurizes normal tap water at pressure levels or more to produce the energy required for slotting. Then, water is focused through the small precise diamond orifice to form an intense cutting stream to create artificial fracturing in coal seam, which has a width of fracturing 30-50mm, and a scope distressed zone of 4-10m [14-15]. Hydraulic fracturing and hydraulic slotting are mainly applicable for brittle or low strength coal seam. Deep-hole pre-splitting blasting technology works by inserting explosives into a pre-constructed borehole and then detonating it to increase seams [16]. Due to the explosion of explosives may cause gas disasters, the technology is not suitable for high-gas mines.

Gas fracturing technology is a kind of burgeoning fracturing technique in China, which fragments material by using highly pressurized gas (air, nitrogen or carbon dioxide) originating from physical phase transition [17-18]. The liquid CO_2 phase-transition fracturing (LCPF) technology is mainly used to fragment coal seam using the energy released from the instantaneous phase change of CO_2 through fracturing boreholes. Due to its advantages of safety, high efficiency, low cost and simple operation, it has been well applied in coal mines, providing a new idea for the treatment of coal mine gas disaster.

2. Engineering Background

The test site was choosed at No. 13 Pingdingshan Coal Mine. The maximum gas content of the current mining seam is 2.89-16.97m^3/t, and the gas pressure is 0.2-3.6MPa. In order to reduce the risk of outburst in coal mines, cross-boreholes and down-seam boreholes are mainly used for gas pre-extraction.

The test working face is 11111 working face in the first mining area, whose elevation is -470~-630m, which is located in the outburst risk area (the area above -450m is the outburst risk area). During the gas pre-extraction period, some boreholes collapse occurred, which seriously threaten the safe production.

3. Boreholes Arrangement and Fracturing Work

The drilling site is located to the east of 220m of the bottom rock roadway of 11111 working face. Drilling through the stratum is adopted to implement fracturing anti-reflection of coal seam of 11111 working face with liquid CO_2 phase transition. In this experiment, three groups of drilling sites A, B and C are arranged. The spacing of drilling sites is 10m. Each drilling site is divided into two fracturing holes, 11 extraction holes, and 13 drilling holes are arranged in two rows with a spacing of 0.5m. Drilling arrangement of bottom drainage roadway through layer is shown in Figure 1.

After the completion of each extraction drilling, the hole shall be sealed and connected to the extraction pipeline immediately. When all extraction drilling holes in each drilling field are completed and the extraction pipeline is connected, the construction and blasting of fracturing holes shall be conducted at an interval of 7 days, and then the hole sealing and gas extraction shall be conducted immediately. After the first fracturing, the second fracturing occurs when the gas concentration or pure gas flow in the adjacent drainage borehole decreases by more than 50%.

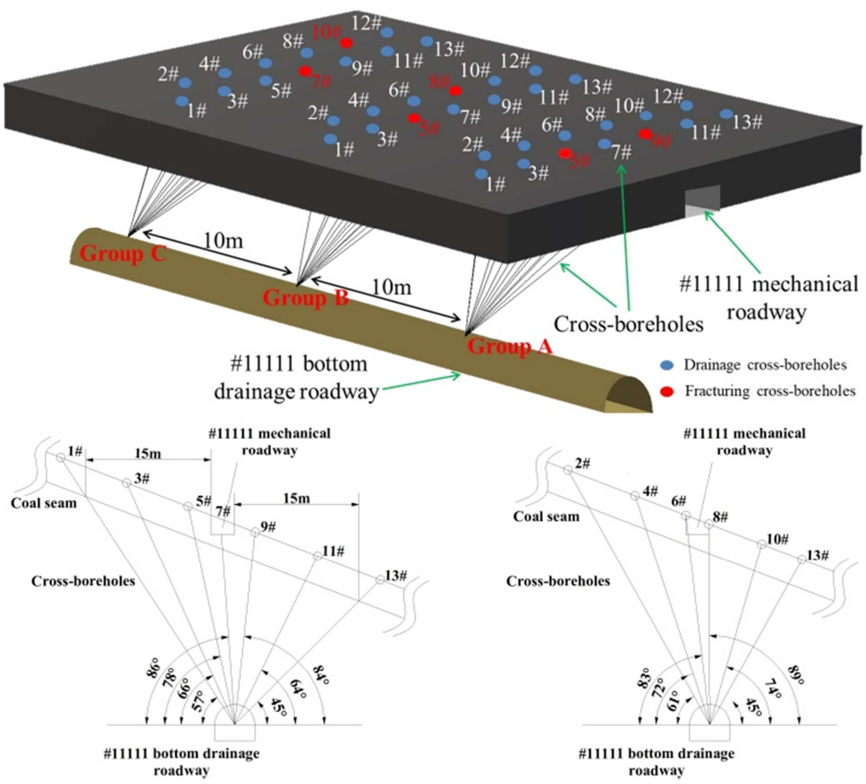


Figure 1. Drilling layout schematic diagram.

4. Results and Analysis

4.1. Effect of Fracturing on Drilling

After fracturing by liquid CO_2 phase-transition, the morphology of the fracturing hole will change under the action of high-energy gas. In order to illustrate the effect of CO_2 fracturing on drilling hole, the hole wall morphology of the fracturing hole at the same depth was observed by a borehole peeping instrument. The result is shown in Figure 2.

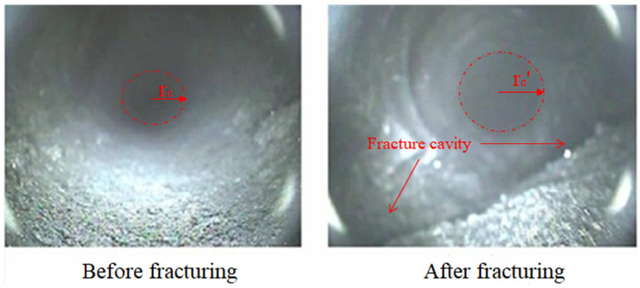


Figure 2. *Comparison of borehole wall before and after fracturing.*

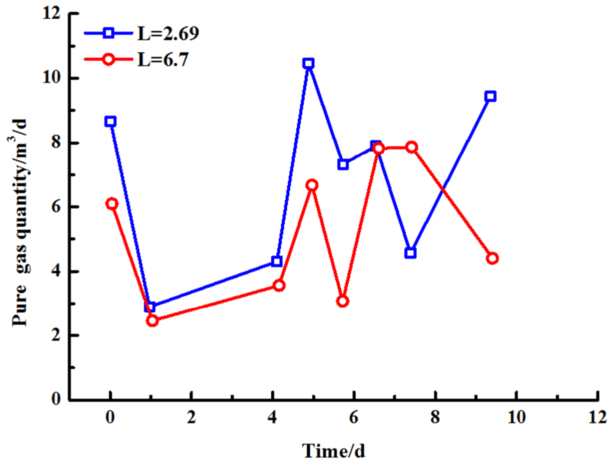
From Figure 2 it can be seen that the borehole wall before fracture is smooth and even, and the borehole diameter after fracture is obviously increased, accompanied by a large number of fracturing and holes, but the borehole still maintain a relatively complete shape, which creates favorable conditions for gas extraction.

4.2. Effect of Fracturing on Gas Extraction Radius

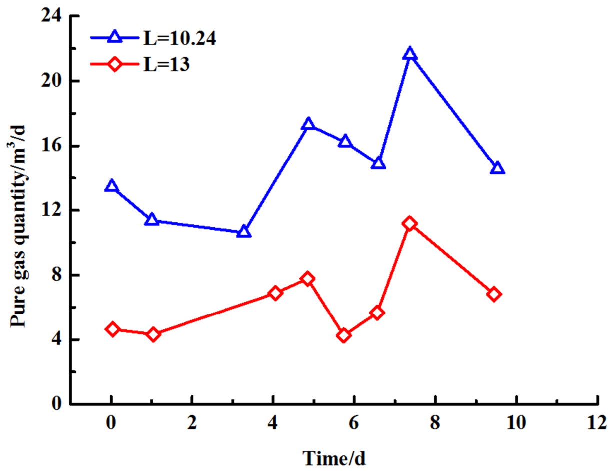
Figure 3 shows the change curve of pure gas quantity in the extraction hole at different distances from the fracturing hole caused by liquid CO_2 phase-transition. It can be seen from the figure that the distance L between the extraction hole and the fracturing hole is an important factor affecting the pure gas quantity in the borehole.

Figure 3 (a) shows that, when the distance between the extraction borehole and the fracturing borehole is less than 7m, the pure gas quantity of the extraction hole after fracturing decreases sharply and stays at a low level for 4h. After 4h, the pure gas quantity of the borehole starts to increase gradually. This is due to the liquid storage pipe releases a large amount of high-pressure CO_2 gas at the moment of fracturing, which compresses the coal around the fracturing hole and reduces the permeability of coal seam. With the passage of time, the compressed coal gradually relaxes and produces many new fracturing, making the pure quantity of gas in borehole gradually increase. According to the statistical analysis of the gas extraction data of the three groups of observation holes, the average compression radius after CO_2 fracturing is 5.6m, and the duration of compression effect is about 4-5h.

At the same time, it can be seen from Figure 3 (b) that: when the distance between the extraction borehole and the fracturing borehole exceeds 10m, the pure gas quantity of borehole in the first 4h does not show an obvious downward trend, that is, the extraction borehole is little or not affected by the compression effect. It can be seen that the influence range of liquid CO_2 fracturing on gas extraction is about 10m.



(a) Distance from fracturing hole, L<7m.



(b) Distance from fracturing hole, L>10m.

Figure 3. *Variation of pure gas quantity in different distances from fracturing hole.*

4.3. Effect of Fracturing on Gas Extraction Efficiency

In order to analyze the effect of liquid CO_2 fracturing on gas extraction efficiency, the continuous data of pure gas quantity and gas concentration in drainage holes are investigated and analyzed, and the variation curves of pure gas quantity and gas concentration in boreholes with time are obtained, as shown in Figure 4 and Figure 5 (the variation characteristics of each borehole are similar, limited to length, only to analyze a set of data).

For the analysis of liquid CO_2 fracturing on the gas extraction efficiency and the effect of the extraction from pure gas quantity and the gas concentration of continuous data analysis, obtained the borehole gas solid flow rate and the gas concentration changing with time curve, as shown in figure 4, figure 5 (the change of drilling features are similar, limited space, only to analyze a set of data).

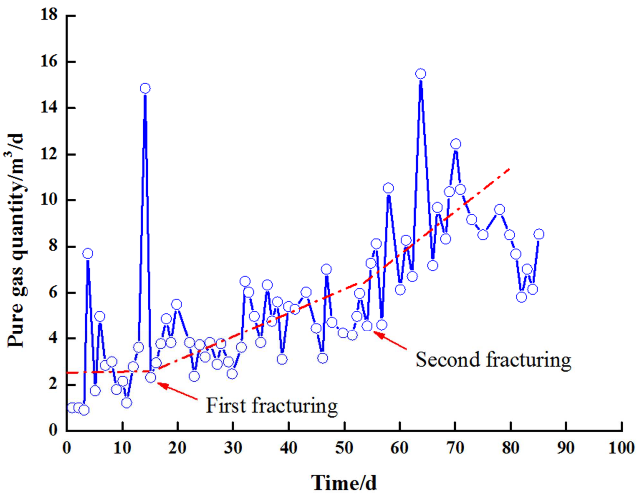


Figure 4. *Variation of pure gas quantity with time.*

From Figure 4, it can be seen that: before the fracturing of liquid CO_2, the pure quantity of gas in the borehole was relatively low, and it showed an obvious attenuation trend with the extension of extraction time. After the first fracturing, the pure quantity of gas in borehole gradually increased, and the overall performance showed an increasing trend with the increase of extraction time. After the second fracturing, the pure quantity gas in borehole increased further, and the increase rate was obviously higher than that in the first fracturing. After the coal seam has been fracturinged twice, the pure quantity of gas in borehole has been significantly increased.

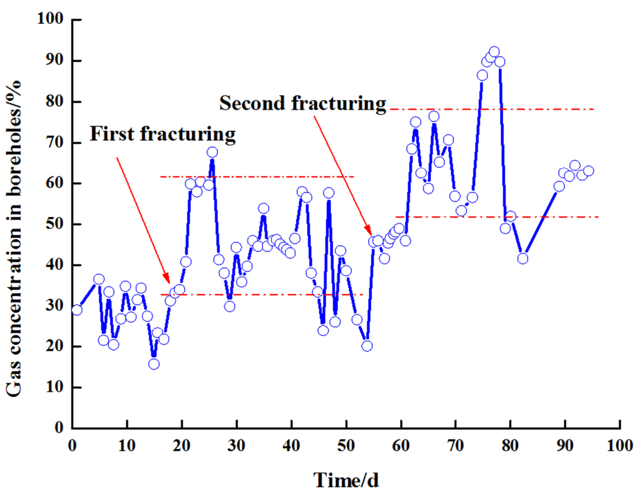


Figure 5. *Variation of gas concentration with time.*

From Figure 5, it can be seen that the gas concentration in borehole presented a step-like upward trend as a result of fracturing caused by liquid CO_2. Before fracturing, the concentration of gas in most boreholes fluctuates between 20% and 40%; after the first fracturing, the fluctuation range of gas concentration in boreholes rises to 30% to 60%; after the second fracturing, the fluctuation range of gas concentration in boreholes further rises to 50% to 80%. The concentration of borehole gas after two pre - fracturing was twice as high as that before pre - fracturing.

In summary, fracturing caused by liquid CO_2 can effectively improve the permeability of coal seam and improve the efficiency of gas extraction in drilling. It should be noted that in the later stage of each fracturing, the pure gas quantity and gas concentration of borehole gas show a certain degree of attenuation, but still remain at a higher level (compared with that before fracturing). This may be caused by the closure effect of fissures over time.

4.4. Compared with Other Anti-reflection Techniques

Figure 6 shows the variation of gas concentration in borehole after different anti-reflection measures are taken in coal seam. It can be seen from figure 6 that, compared with ordinary boreholes, no matter what anti-reflection measures are adopted, gas extraction efficiency can be effectively improved, and gas concentration can be maintained at a relatively high level within a certain period of time, which is conducive to gas extraction. In the 17 days before extraction, the gas concentration after CO_2 fracturing was obviously higher than that of hydraulic punching, with the average gas concentration of 56.9% and 42.4% respectively. In the following month or so, the gas concentration after hydraulic punching was higher than that caused by CO_2 fracturing, 21.4% and 16.7% respectively. This phenomenon shows that there are many fracturing in the coal seam at the initial stage of CO_2 fracturing, which increases the permeability of coal seam and the gas concentration. With the passage of time, under the action of in-situ stress compaction, the fracturing and holes generated by fracturing gradually close, the permeability of coal seam gradually decreases, and the gas concentration decreases accordingly.

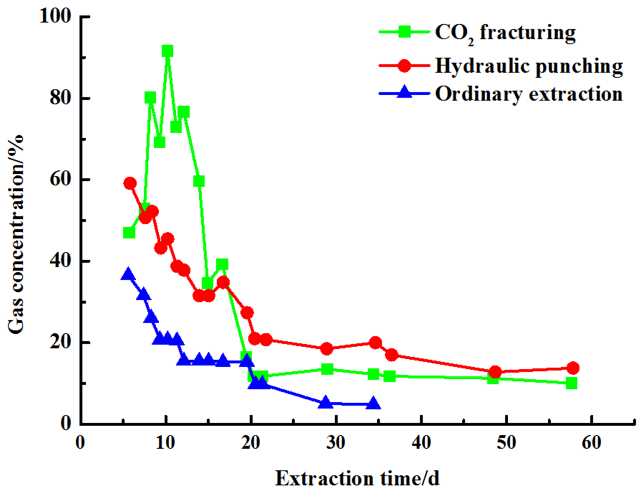


Figure 6. *Comparison of effects of different stimulation techniques.*

4.5. Evaluation of Comprehensive Effect of Fracturing Gas Control by Liquid CO_2

Table 1 shows the changes of related parameters before and after fracturing of liquid CO_2. It can be seen from table 1 that the average gas content and maximum gas emission in coal seam after fracturing by liquid CO_2 have been reduced by 4.73m^3/t and 2.02m^3/min respectively, indicating that liquid CO_2 fracturing technology can effectively improve the permeability of coal seam and thus reduce the outburst risk of coal seam. Drilling cuttings gas desorption index is an important parameter to evaluate the gas outburst tendency of mine. It can be seen from table 1 that after fracturing, this index has been reduced by one level, which can meet the requirements of mine safety production. At the same time, the daily tunneling footage of the mine increased by 3.3m/d after fracturing, greatly shortening the tunneling period. It can be seen that the adoption of liquid CO_2 fracturing anti-reflection technology can bring significant safety and economic benefits to the mine

Table 1. *Changes of related parameters before and after fracturing.*

Gas correlation index	Before fracturing	After fracturing
Average gas content of coal seam (m^3/t)	12.41	7.68
Maximum gas emission (m^3/min)	5.5	3.48
Gas desorption index of drilling cuttings (k_1)	0.40-0.42	0.32-0.33
Tunneling footage of day (m/d)	2.4	5.7

5. Conclusion

1) When LCPF technique is used, high-pressure gas can be generated, which can produce compression effect around the fracturing borehole. The average compression radius is 5.6m, the duration of compression effect is about 4-5h, and the influence radius of gas extraction is about 10m.
2) The gas extraction efficiency of coal seam has been significantly improved after LCPE. Although the gas extraction efficiency in the later stage of each fracturing has decreased to some extent, it still remains at a high level.
3) By comparing and analyzing the stimulation effect of LCPF and hydraulic punching technology, it is concluded that the stimulation effect of LCPF is significant at the initial stage of fracturing, while hydraulic punching is dominant at the later stage.
4) The LCPF technique can effectively improve the efficiency of gas drainage, and thus shortening the driving period of roadways, which has significant economic benefits.

Acknowledgements

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