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Pulsating hydraulic fracturing technology in low permeability coal seams

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ABSTRACT

Based on the difficult situation of gas drainage in a single coal bed of high gas content and low permeability, we investigate the technology of pulsating hydraulic pressure relief, the process of crank plunger movement and the mechanism of pulsating pressure formation using theoretical research, mathematical modeling and field testing. We analyze the effect of pulsating pressure on the formation and growth of fractures in coal by using the pulsating hydraulic theory in hydraulics. The research results show that the amplitude of fluctuating pressure tends to increase in the case where the exit is blocked, caused by pulsating pressure reflection and frictional resistance superposition, and it contributes to the growth of fractures in coal. The crack initiation pressure of pulsating hydraulic fracturing is 8 MPa, which is half than that of normal hydraulic fracturing; the pulsating hydraulic fracturing influence radius reaches 8 m. The total amount of gas extraction is increased by 3.6 times, and reaches 50 L/min at the highest point. The extraction flow increases greatly, and is 4 times larger than that of drilling without fracturing and 1.2 times larger than that of normal hydraulic fracturing. The technology provides a technical measure for gas drainage of high gas content and low permeability in the single coal bed.

1. Introduction

Gas extraction in the pre-exploitation zone is the main measure used to ensure safety in production, realize simultaneous extraction of coal and gas and reduce environmental pollution [1]. Gas occurrence in China has the characteristic of micro-porosity, low permeability and high adsorption, which leads to difficulties in gas extraction [2]. In a single seam without a mining protected layer, although conventional pressure relief and permeability improvement measures are effective, they are unable to meet the actual needs of intensive production in current mines.

Industrial testing of underground hydraulic fracturing technology was introduced in some domestic mines, which provides a new way for gas control in low permeability coal seams and governance of outbursts without protective seam mining. Hydraulic fracturing technology has the characteristic of increasing coal seam permeability, reducing stress and increasing pressure relief [3,4]. Zhao put forward the frequency pulse type methods for coal seam effusion and obtained good effusion effects [5]. Man independently researched the use of high pressure pulse water hammer for water injection, which proved that pulsating type high pressure water injection technology can effectively enhance the permeability of coal seam, and increase the gas drainage quality [6]. Meng injected pulsating water at high pressure into a coal seam to reduce or eliminate the risk of outburst [7]. Hydraulic fracturing technology could improve gas extraction rates in the CBM industry aboard [8–10]. Conventional hydraulic fracturing, which injects high pressure water (usually more than 25 MPa) at high flow rates into the target coal seam, usually causes poor controllability and local stress concentration. Although proper security measures are taken, high pressure is still a great hidden danger for the safety of the operating personal and equipment.

In this article, a pulsating pressure formation mechanism is obtained by analyzing the motion process of a plunger pump, and the effect of pulsating pressure on the formation and growth of fractures in coal is analyzed according to the pulsating pressure analysis method. Pulsating hydraulic fracturing technology in low permeability coal seams is thereby established.

2. Mechanism of pulsating hydraulic fracturing

High pressure pulse fracturing uses pulses from a high pressure pump to provide water pressure fluctuations in the coal to form a water hammer, or “water wedge”, effect which increases the

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porosity of coal, at the same time communicating with original cracks and increasing the coal gas permeability coefficient that provides new flow channels for the gas [11].

2.1. Formation principle of pulse

The structure of a crankshaft plunger pump is adopted as the main part of the pulsating hydraulic fracturing pump for easy operation and maintenance [12]. Based on the motion process of a crankshaft plunger pump, the plunger quantity and structure of a crankshaft plunger pump are determined.

In the actual process, there are flow pulses due to the transient variation of the pump caused by the transient variation in cylinder speed. The transient variation flow can be expressed as [13]:

$$Q_h = kA\omega \sin(\omega t) \tag{1}$$

where k is crank radius; ω is the drive shaft angular velocity; and A is the cross-sectional area of the plunger. This shows that transient variation flow and drive shaft angular velocity present a sine function regulation.

For characterization of the pulsation situation, the flow pulsation ratio is introduced, which can be described as in formula (2).

$$\delta = \frac{Q_{\max} - Q_{\min}}{\frac{1}{2}(Q_{\max} + Q_{\min})} = 2\tan^2\frac{\pi}{4}100\% = 200\% \tag{2}$$

Although a single plunger pump has large pulse intensity, the flow pulsation ratio is low, which is not fit for field application. The flow pulsation ratio of triplex pumps is only 13.9% [13]. A double plunger crankshaft pump was chosen as the pulsating hydraulic fracturing pump producing a pulse pressure of 0–25 MPa. The pulse frequency is 5–25 Hz and the output flow is 120 L/min.

2.2. Mechanism of pulse wave propagation in cracks

Breakage occurs along cracks and joint faces which contribute to the formation of an intricate network of cracks and finally leads to the fracture of a coal seam with a mass of cracks. Intensive pulsating flow promotes larger fluctuating pressures in the cracks along the borehole by propagation and superposition of waves in the cracks. From this point of view, pulse pressure plays an important role in the formation and propagation of cracks in a coal seam [14].

Fiorotto and Rinaldo firstly proposed a transient flow model that treated the pulse wave propagation process as a volatility process or a transient process [15].

$$\begin{aligned} &\frac{\partial h}{\partial t} + v\frac{\partial h}{\partial x} + \frac{a^2}{g}\frac{\partial v}{\partial x} = 0 \\ &\frac{\partial v}{\partial t} + v\frac{\partial v}{\partial x} + g\frac{\partial h}{\partial x} + R(v)v = 0 \end{aligned} \tag{3}$$

where h is the average pressure head of pulse flow; v is the average velocity of fluid in the crack; a is the velocity of propagation of pressure wave; a is approximately a constant; g is the gravitational acceleration; $R(v)v$ is the resistance term and $R(v) = \frac{\lambda}{4\delta}|v|$ is the resistance parameter (λ is the specific blockage factor of the crack, and δ is the thickness of the crack).

The main objective of hydraulic fracturing was to form or connect the cracks with pulse pressure water during the hydraulic fracturing process, which can be simplified as fluctuating water pressure spreading in a blind-ended crack. Numerical solution and laboratory simulation have already been done by predecessors, as shown in Figs. 1 and 2.

From the regularity obtained by analysis and numerical calculation, on the premise of the closing of the outlet port, pressure has a reflexive function in the closed end. The natural frequency and amplitude of the pulse pressure appear to be amplified in the process of spreading. This phenomenon exerts very important effects on the propagation of cracks in the coal seam. Since the initial crack of pulse fracturing is fine, the resistance term has a great influence on the pulse pressure.

Firstly, a two-dimensional capillary model is made to simulate the simplified crack, and the hypotheses are as follows:

(1) The coal seam is modeled as an isotropic and homogeneous solid;
(2) The coal seam contains no water and the flow is single-phase;
(3) The pore texture and cracks are stable.

In Fig. 3, ρ is the density of water; A is the square of the crack; C is the velocity of the pressure wave; V_0 is the velocity of initial flow; ΔV is the change in the velocity; and ΔH is the change in the pressure head. The momentum balance equation for the abrupt change of pulsating water flow in the crack is given below.

$$-\rho g\Delta HA \pm F_f = \rho A(V_0 + \Delta V)^2 - \rho AV_0^2 + \rho A(C - V_0)\Delta V \tag{4}$$

$$\text{Pulse water pressure} \pm \text{surface viscous friction force} = \text{inlet momentum-outlet momentum} + \text{internal momentum(unit time)}.$$

where $\frac{V_0}{g}\Delta V$ is an infinitesimal of higher order term and ΔV^2 is ignored, so that the equation can be converted into the following form:

$$\Delta H = -\frac{C}{g}\Delta V \pm \frac{F_f}{\rho gA} \tag{5}$$

This equation indicates that an extra term, $\frac{F_f}{\rho gA}$, is added to the change of amplitudes of pore pressure due to viscous friction, which is in direct proportion to the viscous friction coefficient. Plus or minus is determined by the direction of flow. When the pulsating water reaches the crack tip, the reflected wave, which is opposite to the flow, has the same sign with $\frac{C}{g}\Delta V$ which leads to the enlargement of pressure in the crack tip.

Research shows that the transient amplitude of pressure has a great influence on hydraulic friction. Friction resistance of unit length h_f' is used to describe the value of frictional resistance.

$$h_f' = \frac{h_f}{L} = \frac{\lambda}{\delta}\varphi^2 \tag{6}$$

where $h_f(\text{linear loss}) = \lambda\frac{L}{\delta}\frac{V^2}{2g}$; λ is linear resistance coefficient; L and δ are the length and width of the crack; and $V = \varphi\sqrt{2gH}$, the flow coefficient.

The results show that the change in amplitude of fluctuating pressure is in direct proportion to the linear resistance and flow coefficient. In the process of industrial tests, cracks occur around the borehole due to the destruction caused by drilling. In general, the cracks are very small; in the process of high pressure pulse water, amplified and alternating pressure is generated at the end of the crack.

2.3. Principle of pressure relief

The tests on the strength of coal under cyclic loading show that the coal at 15.88 MPa stress for 625 times of circulation at a frequency of 0.5 Hz was damaged irreversibly; the tests on the strength of coal under cyclic loading show that the coal at 23 MPa stress for 198 times of circulation was damaged irreversibly [17]. Pulsating hydraulic fracturing at pressures in

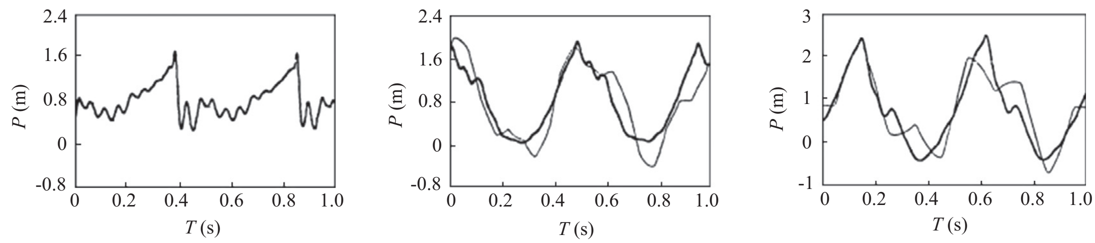

Fig. 1. Pulsating pressure with time on closed-cup conditions (Solid lines indicate experiment and thin lines calculation) [14].

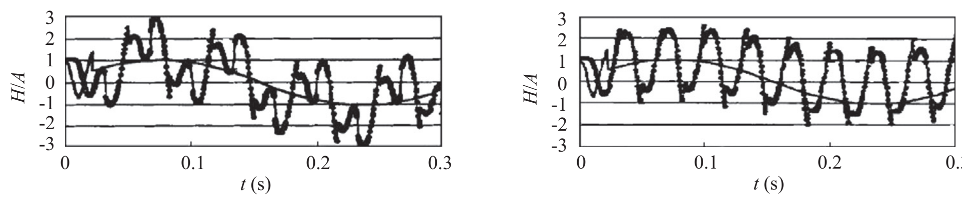

Fig. 2. Pulsating pressure with time on closed-cup conditions (Solid lines indicate pulsating pressure and thin lines initial pulsating pressure) [16].

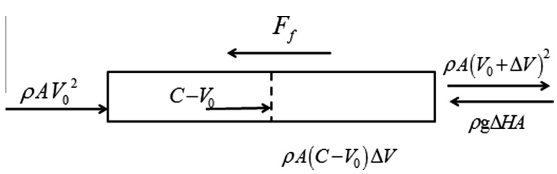

Fig. 3. Diagram of control volume and force.

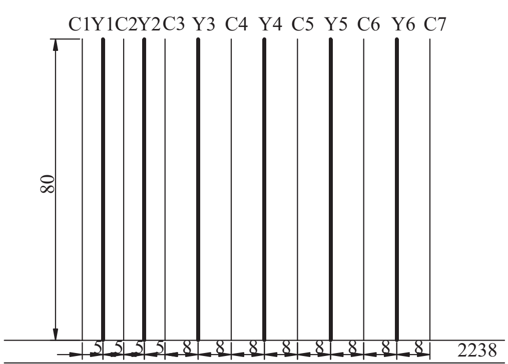

Fig. 4. Drawing of hydraulic drillings in tunnel of 2238 (m).

the range 0–25 MPa, frequencies of 5–25 Hz and lasting 35–50 min could damage the coal.

3. Field tests

The field test site is located at the 2238 auxiliary drift in Chengzhuang coal mine.

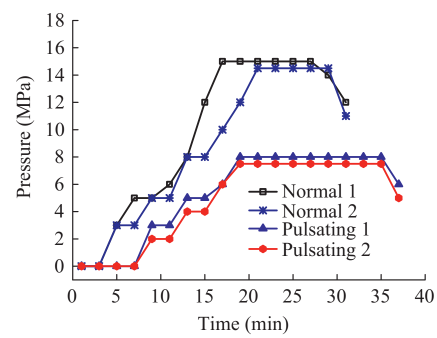

Fig. 6. Hydraulic fracture pressure with time.

3.1. Pulsating hydraulic fracturing technology and parameters'

The coal bed in 2238 auxiliary drift has the characteristic of a burial depth of 480 m, the gas content is 12–14 m^3/t, the original gas pressure is 0.52 MPa, and the coal seam roof and floor are sandy mudstone, without geological structure around the construction site. In order to improve the coal gas permeability and the gas extraction effectiveness, the pulsating hydraulic fracturing borehole was set up in 12# traverse in 2238 auxiliary drift. In order to investigate and verify hole sealing effects, the distance between the initial pulsating hydraulic fracturing hole and the extraction hole is from 5 m extended to 8 m, as shown in Y1 and Y3 of Fig. 4. Y5 is a conventional hydraulic fracturing hole and Y2, Y4 and Y6 are pulsating hydraulic fracturing holes.

The hydraulic fracturing system mainly includes an electric machine, emulsion and pulse pump, water tank and relief valve, as shown in Fig. 5. Hydraulic fracturing ended when water gushed from drainage holes or the pressure dropped abruptly.

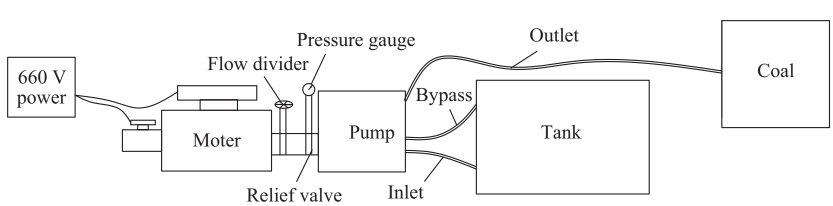

Fig. 5. General view of high voltage pulsating hydraulic fracturing system.

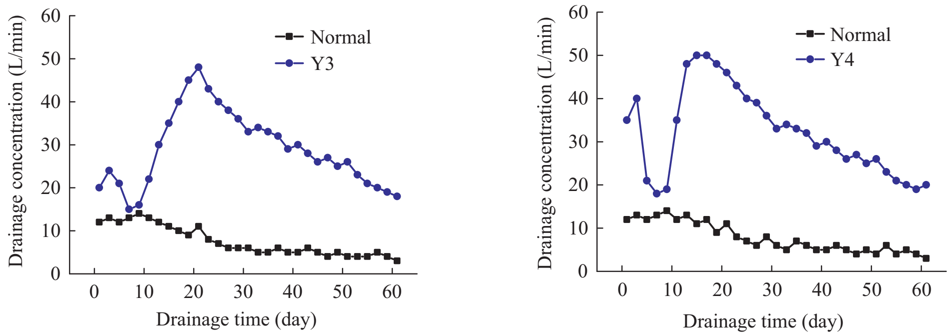

Fig. 7. Contrast diagram of gas extraction flow of hydraulic and pulsating hydraulic fracture drilling and normal drilling. (a) Hydraulic fracture. (b) Pulsating hydraulic fracture.

3.2. Analysis of field test parameters

In order to verify the pulsating hydraulic fracturing effect, a BRW200/31.5 type emulsion pump and high pressure pulse pump were used, and the time and the pressure of hydraulic fracturing were investigated, as shown in Fig. 6.

The field test comparison shows that the maximum pressure in the pulse pump is 8 MPa and the maximum pressure in the emulsion pump is 15 MPa. It is shown from the analysis of the changes of pressure that in the primary stage which is 7 min for the pulse pump, the hole and pre-existing fractures were filled with fracturing fluid at a pressure 0 MPa. By the end of the primary stage, the injection pressure escalated. In order to ensure the hydraulic fracturing effect, the conventional hydraulic fracturing pressure was maintained for about 3–5 min at 3 MPa, 5 MPa, 8 MPa and the pulsating hydraulic fracturing pressure was maintained for about 3–5 min at 3 MPa, 5 MPa, along with the accumulation of energy, crack developed progressively. It is shown that the gage pressure, which was 14.5–15 MPa for the emulsion pump and 7.5–8 MPa for the pulse pump, was the initial pressure of the coal seam, when the pressure did not increase with time. The crack at this stage is in steady growth while the duration is related to the hydraulic fracturing distance and flow of the pump. In 2238 auxiliary drift it lasted for 30–40 min. By analysis of the fracturing process, we can conclude that at the site, a pulse pump hydraulic fluctuating pressure of 8 MPa and conventional fracturing at 15 MPa have the same effect on the premise of guaranteeing safety.

3.3. Quantity of drainage

According to statistics, after removing the abnormal value, investigations of the drainage parameters of pulsating hydraulic fracturing boreholes, conventional hydraulic fracturing boreholes and drainage boreholes without hydraulic fracturing and selecting Y3 and Y4 are shown in Fig. 7.

By contrast analysis of Fig. 7a and b, it is shown that these hydraulic fracturing measures can greatly improve the gas drainage quantity. The maximum gas drainage quantity from conventional hydraulic fracturing is 48 L/min and the maximum gas drainage quantity of pulsating hydraulic fracturing is 50 L/min, which is 3.6 times the quantity of gas from drainage boreholes without hydraulic fracturing. The total quantity of drainage by pulsating hydraulic fracturing is 4 times larger than that of boreholes without hydraulic fracturing over 60 days.

The gas drainage quantity presents a decreased area within 4–8 days, but it builds up quickly. The reason is the water locking effect [18] which means that foreign water intruded the coal and could not be effectively eliminated over a short time, leading to an increase in water saturation and the decline of gas permeability. Under the drainage negative pressure, the water locking effect weakened gradually and the gas drainage quantity rose with the passage of time. Because the pulse pump flow is smaller than that of the emulsion pump, the water locking effect caused by the pulse pump is weaker than the emulsion pump.

4. Conclusions

(1) In fissures, the phenomenon of amplification of frequency doubling is found in the process of fluctuating pressure propagation. Where the ends of fissures are closed, due to baro-reflex and superimposed frictional resistance, the amplitude of the fluctuating pressure will be increased in the passage of fissures, thus smaller fluctuating pressures can also cause fissure destruction.

(2) Pulsating hydraulic fracturing can increase the porosity of coal, at the same time linking pre-existing fractures, which forms a network of related fractures, increases the coal gas permeability coefficient and provides new gas flow channels. Both pulse hydraulic fluctuating pressure of 8 MPa and conventional fracturing of 15 MPa have the same effect. The maximum gas drainage quantity from a single hole is 50 L/min, which is 3.6 times larger than that of a conventional hole in pulsating hydraulic fracturing. In the first 60 days, the drilling extraction quantity of pulsating hydraulic fracturing is 4 times larger than that of non-hydraulic fracturing, which enhances production efficiency on the premise of guaranteeing safety.

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