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Pulsating hydraulic fracturing technology in low permeability coal seams

Wang Wenchao [a], Li Xianzhong [b,c,*], Lin Baiquan [c], Zhai Cheng [c]

[a] School of Civil Engineering, Tianjin University, Tianjin 300072, China
[b] School of Energy Science and Engineering, Henan Polytechnic University, Jiaozuo 454000, China
[c] School of Safety Engineering, China University of Mining and Technology, Xuzhou 221116, China

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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

* Corresponding author. Tel.: +86 15138010712.
E-mail address: 15138010712@163.com (X. Li).

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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