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Fracturing mechanism of coal-like rock specimens under the effect of non-explosive expansion

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A R T I C L E I N F O

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A B S T R A C T

A non-explosive expansion method (NEM) is proposed to apply in the field of reservoir fracturing for the extraction of coalbed methane. Specimens with mechanical properties similar to primary coal were prepared, and their fracture behavior was investigated under different side stresses. Acoustic emission (AE) and infrared thermal imagery were utilized to record the parameters (energy and amplitude) of the AE events and the surface temperature distributions, respectively. The results showed that specimens were all destroyed using NEM with different crack morphologies under diverse side stresses, and the fracture evolutions were greatly dependent on the structure and side stresses, which caused complex crack numbers and crack distributions. Several periodic energy concentrations and the stair increasing pattern of cumulative energy all indicated that the fracturing process of NEM did not finish instantaneously but continued for a long time. A quantitative analysis of crack number and distribution by box counting showed that the larger the number of fractures, the greater the fractal dimension and the greater the complexity, and the difference in fracture density positively correlated to the fractal dimension was influenced by side stresses. Fractures might be determined by the coupled effect of swelling force and released heat according to the chemical reaction of agents. The relationship between swelling force and tension stress was deduced based on the thick-wall cylinder theory. A semi-submersion test was carried out to evaluate the effect of released heat on crack generation preliminarily in consideration of material volume and influence time. The greater material volume and longer influence time created a number of blocks and produce complex crack faces, largely related to the released heat inducing a complete temperature gradient.

1. Introduction

Throughout the world, conventional energy sources such as coal and other fuels have been utilized for many years and have been contributing to the energy crisis and environmental problems.[1–4] Currently, many countries are expanding into more modern energy resources by enlarging exploration into unconventional resources such as coalbed methane (CBM) and shale gas, and gradually increasing their proportion of consumption.[5–12] In China, substantial quantities of unconventional resources are stored in dense reservoirs, which have low permeability because of their burial depth and lithological character,[13–15] which presents significant obstacles to the extraction and utilization of these resources. To improve the extraction efficiency, the reservoirs will require fracture stimulation using fracture generation and ‘anti-reflection’ techniques (namely, increasing the amount of fracture and improving the permeability technology) to increase the number of flow-paths and finally form a complex fracture network.[6,7,9–12,16]

Aiming at permeability enhancement, universities and scientific research institutions in many countries recently have formed two main research interests: deep hole blasting by an explosive or liquid gas,[17–20] and hydraulic measures.[21–23] Some achievements have been attained. However, some limitations exist in field application. Gas ignition may be caused by borehole blowouts in deep holes, and misfired cannons can also be a potential risk;[24] additionally, hydraulic measures are always complex, involving a complicated operation, strict sealing requirements, and difficult equipment mobility.[25]

In contrast, a non-explosive expansion method (NEM) has been used for the last forty years and appears to have been developed by Onoda Cement in Japan.[24,26] NEM works by filling a borehole in advance with a static cracking agent (SCA), followed by an expansion in volume during the chemical reaction of the SCA. This process causes material surrounding the SCA to break.[27] The properties of SCA have been

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investigated by many scholars,[28–31] and it has been found that the main factors influencing the swelling force of SCA include borehole size, water-cement ratio and external temperature. This method has distinct advantages over active blasting, such as stable performance, a simple operation, a lack of flames/detonation, and no development of projectiles.[32] This method is applicable in mining, quarrying and demolition.

Gambatese 30 analyzed controllable fracture behavior in concrete on a small scale using SCA, concluding that SCA was a feasible method for rock fracturing. Li et al. 33 also investigated the feasibility of using anti-reflection techniques to fracture coal seams by combining NEM with an appropriate layout of boreholes. Tang et al. 34 studied SCA-induced fracturing in concrete blocks by conducting physical experiments, and confirmatory two-dimensional (2D) modeling using rock failure process analysis (RFPA) to demonstrate crack development during initiation, growth, and final unstable extension. Lai et al. 35 conducted an investigation on weakening and fracturing specimens by static blasting using acoustic emission (AE) and recorded results photographically. Their experimental results were of particular significance in improving the technology and furthering the engineering application of this technique to advanced fracturing of steep coal roofs.

Tang et al. 36 employed SCA demolition to fracture coal seams with low permeability, and the agents with an optimized proportion ratio fractured briquettes. The maximum width of the cracks reached 16.33 mm, indicating significant potential for improving low permeability coal seams. The fracture mechanism associated with SCA in single and multiple holes was explored to improve the extraction efficiency of CBM by investigating the optimum layout of the boreholes. Hao et al. 37 studied the physical laws that govern the evolution of cracks in limestone masses under uniaxial stress caused by static blasting. Guo et al. 38 developed a method for assessing the features of SCA-induced fractures, and investigated the formation process of fracture networks in shale with different degrees of rigidity and brittleness via dynamic monitoring of acoustic emission (AE) events. Their results proved that SCA has a significant potential application in unconventional reservoirs for efficient extraction.

The published works described above all indicate that SCA has significant fracturing capacity because of its swelling force, and has been applied in many fields. However, most studies have focused on the fracturing process of the specimens without assessing the effects of side stress or the effects of released heat during the reaction of SCA.[32] Thus, the experiment of NEM, against the background of CBM extraction, with four different side stress coefficients (k) was carried out. To simplify the research objects, specimens were prepared with similar mechanical properties to primary coal. AE and infrared thermal image were used to monitor the AE events and the values and distribution of surface temperature respectively. Fractal dimension and fracture density were used to quantitatively characterize the complexity and distribution of cracks; the effect of swelling force and temperature stress were comprehensively analyzed. The experimental results provide theoretical support for further research on the fracturing process in unconventional resource reservoirs.

2. Experimental work

2.1. Experimental equipment

An experimental system is developed and adopted in this study, as shown in Fig. 1. The load simulation system, which adopts a hydraulic servo control system, is used to provide various confining pressures. The AE monitoring equipment is employed to monitor in real-time and record AE events using a suitable AE detector.[39–42] The detailed information of the AE setup is as follows: the sampling rate is 5 MHz by synchronal acquisition for many sensors; the accuracy and nonlinear error of A/D conversion are 16 and ± 0.5 LSB, respectively; the usage temperature range is from 253 K to 333 K; the amplifier gain value is 100; the output noise is 26.4 db; and the output and input impedance are 50 Ω and greater than 10 MΩ, respectively. In addition, infrared thermal imaging system equipped with an uncooled focal-plane array thermal imagery, type DaLi 700E+, was used to dynamically monitor the temperature change of surface radiant heat distribution.[43–45]

2.2. SCA and specimen preparation

The modified type A SCA selected for this study is mainly composed of calcium oxide (CaO) and some other inorganic compounds, such as iron sesquioxide, silica, and aluminium oxide. The stipulated temperature range used was 285 K to 298 K. The SCA produces an exothermic chemical reaction with water, generating $Ca(OH)_2$ after CaO contacting with water, and the microscopic volume progressively increases. As the reaction continues, $Ca(OH)_2$ gradually fills in the voids within the finite space and produces swelling force to the space border.

As coal belongs to the heterogeneous brittle materials, there are many defects, such as tectonic coal loss and fragile phenomena, when the coal is cut as large size blocks. We therefore chose specimens with mechanical properties similar to primary coal, and these specimens were blended using cement, sand, coal powder, plaster powder, and water in the proportion of 2:1:1:2:2.[46] The used molds were pre-sprayed in the interior with a releasing agent. The blended material slurry was poured into the molds and stirred using a vibrator to eliminate air. Then, the specimens were placed in curing chamber for 30 days to form briquette specimens with a side (L_1) of 250 mm. The mechanical testing results of different sizes of cores from selected specimens were shown in Table 1, the compressive strength, tensile strength, and shear strength of the specimens were 18.2 MPa, 0.74 MPa, and 3.73 MPa, and the errors were 1.1%, 9.3%, and 0.8%, respectively, which indicated that the prepared specimens were closed to the raw coal rock.[46]

2.3. Experimental procedure

According to relative literatures[47,48] and the applicable temperature, the experimental temperature is 285 K and the laboratory humidity is 20%. The background adopted method of counter light, and the procedure was as follows:

(1) *Drill an appropriate borehole*. To eliminate the boundary effect, the principle of large specimen and small borehole was adopted. So, borehole with diameter of 20 mm and depth of 180 mm (L_2) was drilled at the center of one side using a coring bit.[47]
(2) *Set the charge powder*. Appropriate material was prepared using a water cement ratio of 0.3 according to Li 49. After mixing and stirring, the charge was conveyed into the borehole and subsequently tamped, as shown in Fig. 2(a).
(3) *Assemble the monitoring system*. To ensure uniform side stress was exerted on the specimens, soft rubber mats were used between the specimen and the press-plate. An unconfined state and three different states of k values, namely, $k < 1$, $k = 1$, and $k > 1$ (shown in Table 2), were carried out. In addition, AE probes 1, 2, 5, and 6 were arranged in regular diagonal lines with a 40 mm distance to the adjacent borders respectively, as shown in Fig. 2(b). When the AE system was connected properly, the threshold value was set to 40 dB and the sampling frequency to 1 MHz. At the same time, infrared thermal imaging was employed to monitor the temperature variation of the free top surfaces.
(4) *Post-processing and data collection*. The specimens were taken out after fracturing to observe the geometrical sizes and numbers of fractures. On this basis, the fractal dimension and fracture density were calculated as part of the analysis and post-processing of the images and AE data.