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Response characteristics of coal subjected to coupling static and waterjet impact loads

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ABSTRACT

We have established an experimental system to investigate waterjet impact capacity and coal relaxation behaviors, with reference to hydraulic slotting. The results indicate that after waterjet impact, cracks with good connectivity can be observed on the surfaces of the coal specimen. Vibration acceleration can intuitively display waterjet impact capacity. The disturbance capacity of waterjet impact is significantly larger than that of drilling. The waterjet disturbance degree is defined by the vibration amplitude to quantitatively describe the waterjet impact capacity. The waterjet disturbance degree presents a decrease tendency after an initial increase with the increase in waterjet impact angle, presents a gradual increase tendency with the increase in the operating pressure, and presents an overall decrease tendency with the increase in the lateral coefficient. Based on the variations in axial and lateral pressures, we also proposed axial and lateral relaxation degree to quantitatively describe the coal behaviors under coupling static and waterjet impact loads. The axial relaxation degree gradually decreases and the lateral relaxation degree presents an opposite tendency with the increase in waterjet impact angle, and presents a gradual increase tendency with the increase in lateral coefficient. The research achievements can provide certain references for the application of hydraulic slotting in underground enhanced CBM recovery.

1. Introduction

The high-speed waterjet has remarkable erosion capability which is characterized by several operational advantages, including high efficiency, heat-free, dust-free and vibration-free performance.[1–3] The initial research of the erosion capability is focused on the waterjet patterns, the target deformation/breakage behaviors, *etc*.[4–8] Based on these fundamental principles, the high-pressure waterjet technique has been applied in various industries such as mining industry, mechanical manufacturing industry, *etc*, and been proved an effective approach due to its extreme simplicity and flexibility.[9–13] The application of this technique in mining activities can be summarized as three aspects: roadway excavation, hydraulic mining and gas drainage. For economical excavation of tunnels and roadways with high efficiency, the mechanical excavation assisted by high pressure waterjet was proposed, and the combination parameters of the mechanical bit and the nozzles was optimized.[14–17] In regards to the hydraulic mining, a feasible method named borehole hydraulic coal mining system was developed, which involves fragmenting coal seams by high-pressure waterjet and removing coal slump through a drilled borehole by hydraulic or air-lifting methods.[18] Recently, Li [19] introduced a novel hydraulic method for underground mining of a thin sublayer as a protective coal seam. This method can overcome the limitations of traditional protective layer excavation technique (e.g. time and cost).

The consensus has been reached about the role of gas drainage in coal mining industry, namely, threefold effect including decreased environmental impact, guaranteed underground workforce safety and the production of a relatively clean energy.[20–24] Suffered from drastic tectonic movements, the majority of coal in China became soft and complicated, which has an adverse effect on the gas migration.[25–28] The stimulation measures should be adopted to enhance the coal permeability. The main idea of the proposed measures up to date is to create the cracks within the coal as much as possible. Hydraulic slotting can significantly improve the coal permeability through formation of pressure relief space via high-pressure waterjet impact on the borehole wall for coal deformation to induce the crack initiation and coalescence.[29–31] According to the research methods, the achievements in hydraulic slotting can be summarized as the following four aspects:

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theoretical analysis, laboratory experiment, numerical simulation and field test. In the aspect of theoretical analysis, the evolution characteristics of the crack field within the coal subjected to high-pressure pulsed waterjet was theoretically analyzed by Lu et al. [32] via the established coal damage model, and the reasonable parameters such as pressure and flux for application of this technique are derived. A mathematical model of gas flow within the slotted coal was established by Shen et al. [33] by dividing the slot affected area into main affected area and boundary affected area, and the criterion for outburst elimination was obtained based on the above model. Recently, a radial permeability model of coal around the slotted borehole was derived by Gao et al. [34] by taking the stress distribution around the borehole and the relationship between the permeability and effective stress into consideration. Laboratory experiment aims at obtaining relatively real conclusion by small-scale physical simulation. Ge et al. [35] conducted a rotary waterjet impact experiment, and the ellipse-shaped slot morphology was obtained. The effect of the slot on the coal permeability is elaborated by Shen et al. [36] via laboratory physical simulation experiments. The results show that the coal permeability around the slots significantly increases with the formation and extension of the slots. Numerical simulation is another crucial method to reveal the potential laws of hydraulic slotting. The $FLAC^{3D}$ software was used to explore the variation in stress field around the slots.[37,38] The PFC^{2D} software was adopted to reveal the change of crack field around the slots.[39,40] The COMSOL software was applied to investigate the variation in gas flow field around the slots.[41,42] The results of above-mentioned numerical simulations show that the slot can substantially relieve the stress imposed on the coal around the slot. The stress redistribution induces numerous cracks formation, propagation and coalescence. The cracks provide plenty of flow channels for gas migration. In this manner, the enhancement of CBM exploitation is realized. The field test can provide a verification for the conclusion of the above-mentioned three methods. The field tests have been conducted in various coal mines, and the results showed that the gas concentration and pure flow increase significantly, which verifies the hydraulic slotting technique is a useful and practical measure to realize the enhanced CBM exploitation.[43,44] In summary, significant achievements have been made regarding hydraulic slotting. However, the previous research mainly focuses on the verification of the feasibility and practicality of this technique. Besides, the real waterjet load is always ignored. Moreover, as the mining depth extends, the crustal stress enlarges remarkably. The behaviors of coal subjected to the coupling waterjet impact and the high crustal stress should be thoroughly investigated to provide a reference for the enhanced CBM exploitation in deep mining level. Based on the above analysis, we have established an experimental system. Then the respond characteristics of the coal subjected to the coupling waterjet impact and high crustal stress are elaborated via this experimental system.

2. Experimental system and scheme

2.1. Experimental system

The main parameters considered in this paper are crustal stress, waterjet pressure and waterjet impact angle. Correspondingly, the research objects include the following three aspects: (i) Quantitatively describe the waterjet disturbance; (ii) Investigate the interaction between the waterjet and the coal; (iii) Elaborate the effect of waterjet parameters and lateral coefficient on coal response to the waterjet impact. Based on the above research objects, an experimental system was developed. As shown in Fig. 1, this experimental system consists of four sections, namely high pressure pump station, pressure control device, dynamic and static load integration device and data acquisition module. The detailed introduction of the four section are as follows.

(i) *High pressure pump station*. The high pressure pump station used in the experimental is the same as the one used in the field test. It is made from the Nanjing Liuhe coal mine machinery limited liability company. Its rated flux and rated pressure are 200 L/min and 31.5 MPa, respectively.

(ii) *Pressure control device*. This device (Fig. 1b) is self-developed. It can accurately regulate the output flow of the high pressure pump station and display the water pressure of the pipe, which is simple and practical.

(iii) *Dynamic and static load integration device*. It is the core part of the experimental system. Its front and back view are displayed in Fig. 1(c). Its physical map is displayed in Fig. 1(d). The device mainly consists of oil cylinder, waterjet generator, angle adjustor and transparent baffle. The oil cylinders are used to impose the axial and lateral pressures on the specimen. The ranges of the axial pressure and lateral pressure are 0 ~ 25 MPa. The channel of the nozzle is straight, and its diameter is 0.5 mm. The waterjet generator can simultaneously eject two symmetrical waterjets. The angle adjustor is applied to adjust the waterjet impact angle. The range of the angle adjustment is 0° ~ 90°. The transparent baffle is used to separate the image capturing device from the residual water cylinder. The angle adjustor is fixed on the waterjet generator. The waterjet impact angle adjustment method is described as follows: (i) Overlap the nozzle with the 0° scale mark of the graduated disk. (ii) Rotate the waterjet generator to overlap the scale mark of the preset angle with the vertical plane.

(iv) *Data acquisition module*. It mainly includes pressure acquisition system and dynamic acceleration acquisition system. The pressure acquisition system is used to monitor axial and lateral pressure in real time via axial and lateral pressure sensors. The dynamic acceleration acquisition is realized by the DH5960 dynamic signal test and analysis device (Fig. 1e) developed by Donghua testing technology limited liability company. This device is characterized by: (i) Real-time multi-channel continuous data acquisition with long period. (ii) Stable high-efficiency data transmission with no drop-out and crash fault. (iii) Four-wire carrier bridge for avoiding the effect of wire length on the bridge voltage. Its maximum sampling rate is 20 MHz, which can meet the requirements of impact and blasting signal monitoring.

2.2. Coal specimen preparation

The coal samples are from Yangliu Coal Mine, China. As shown in Fig. 2, the coal samples were cut into cubic specimens with the size of 150 mm × 150 mm × 30 mm. The detailed coal parameters such as moisture, ash, volatile matter and fixed carbon contents can be found in our previous research.[3,29] The pretreatment of the coal specimens were conducted. The pretreatment method is described as: (i) Evenly spray the white paint on the surface of the coal specimen. (ii) Put the iron plate with circular holes on the white surface of the coal specimen. (iii) Evenly spray the black paint on the iron plate. Finally, the coal specimen surface is coated with a white thin paint and evenly distributed black circular point, which attributes to the observation of the crack behaviors in the whole experiment. As shown in Fig. 3, two acceleration monitoring sensors with the internal of 30 mm are arranged along the waterjet impact direction on another surface of the coal specimen. The angle between the waterjet impact direction and the horizontal plane is labeled as β.

2.3. Experimental scheme

Three variables, namely waterjet impact angle β, lateral pressure coefficient K and operating pressure p, are considered to conduct experimental design. As listed in Table 1, the coal specimens are labeled as "lateral pressure coefficient K + waterjet impact angle β". It should be noted that the lateral pressure coefficient K are defined as: