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Increasing permeability of coal seams using the phase energy of liquid carbon dioxide

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ABSTRACT

Carbon dioxide (CO_2) is a major greenhouse gas, and it is also an energy source that can be utilized. This paper describes a new technology designed to increase the permeability of coal seams using the phase energy of CO_2. The technology, named as liquid carbon dioxide phase change fracturing technology, is classified as physical blasting. The kernel of this technology is the blasting system, which consists of release tube containing release holes, cutting plate, liquid storage tube containing heating pipe, guide tube and detonator following the order from the top to the bottom. By starting the detonator, special chemicals in the heating pipe begin to react and a lot of heats then are released instantly to heat the liquid carbon dioxide in liquid storage tube. This process brought about the phase change of carbon dioxide and then caused the dramatically expansion of the volume of carbon dioxide. When the pressure of carbon dioxide in the liquid storage tube exceeds the strength of the cutting plate, the cutting plate is damaged and high pressure carbon dioxide enters the release tube and acts on the coal body. The sphere of influence of this technology in coal seams was studied by the numerical study. Then, a large-scale industrial experiment using the technology was conducted in an underground coal mine in China based on the modeling results. Application of this technology could not only improve the efficiency of coal seam gas extraction but could also turn carbon dioxide into energy to improve energy efficiency.

1. Introduction

As the world has continued to develop, the conflict between environmental protection and energy resource has emerged [1]. Coal is the main energy source of China and accounts for 67.4% of the total energy consumption [2–5]. In China, too much coal consumption contributes to a large portion of methane emission. Other than carbon dioxide (CO_2), methane (CH_4) has been the greatest radioactive force among the greenhouse gases [6]. Therefore, controlling methane emission during coal mining is very important for the environment.

Gas pre-drainage in the coal seam is an effective way to control gas emission and capture the gas source in coal mines [7–9]. However, low permeability, high gas pressure and high in-situ stress around the coal seam have restricted gas drainage work in most Chinese mines. For mines possessing coal seam groups, mining the protective coal seam is an effective means to improve the gas drainage effect [10,11]. However, to improve gas drainage for a single coal seam requires that measures be taken to increase its permeability. Presently, single coal seam reinforcement drainage measures include hydraulic slotting, hydraulic fracturing, and dynamite blasting.

Lu et al. [12,13] and Shen et al. [14] described the development of hydraulic cutting technology for hydraulic slotting and analyzed mechanisms to improve the permeability of coal seams by hydraulic cutting. They also illustrated the feasibility of applying the technology in practical engineering. Additionally, Zou et al. [15] studied gas adsorption characteristics of coal after hydraulic slotting.

Hydraulic fracturing is commonly used to increase the permeability of coal seams. Li et al. [16] introduced the effect of pulse frequency on crack expansion and concluded that high frequency was more successful in generating cracks. Zhai et al. [17] proposed the method of directional hydraulic fracturing and proved the feasibility of this method through field testing. Yan et al. [18] indicated that a complete pressure relief zone, a transitional pressure relief zone and the original stress zone would be

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generated around the borehole after hydraulic fracturing. Through numerical simulation, Yang et al. [19] and Zhang et al. [20] concluded that the mechanical properties of rock cracking had an important influence on the initiation and incrementation of cracking during hydraulic fracturing. Zhang et al. [21] also established a hydraulic fracturing model and analyzed the influence of hydraulic fracturing on gas desorption and diffusion.

Guo et al. [22] proposed the method of using dynamite blasts in the borehole to increase the permeability of the coal seam, and they obtained the effective influence radius. Zhou et al. [23] and Cai et al. [24] hypothesized that dynamite blasts in the borehole could improve the effect of gas drainage and eliminate the risk of coal and gas outbursts. Liu et al. [25] analyzed fracture and stress evolution characteristics during directional blasting using a test directional blasting system. Additionally, Zhu et al. [26,27] and Zhu et al. [28] discovered that dynamite blasts in the coal seam could not only eliminate stress concentration around the borehole but also could increase the permeability coefficient of the damage zone of the coal body around the boreholes.

Hydraulic slotting, hydraulic fracturing and dynamite blasting in coal seams all had a beneficial effect for improving coal seam permeability. However, there were also disadvantages. Jet orifices were prone to occur during hydraulic slotting and fracturing, and working conditions and experimental equipment were poor and complex. In addition, the process of dynamite blasting in the coal seam often resulted in the presence of unexploded dynamite, creating hazards for coal mining. The blasting power of dynamite was difficult to control, and the transportation and management of dynamite were also very difficult.

CO_2 is a greenhouse gas. The greatest potential for reducing CO_2 emissions is carbon capture and storage (CCS) and carbon capture and utilization (CCU) [29–32]. Compared with CCS, CCU can not only reduce CO_2 emissions but also can produce valuable fuels and chemicals that will enable the petrochemical industry to recoup the costs of CO_2 capture and conversion [33,34]. In this paper, liquid carbon dioxide phase change fracturing technology previously used in the underground excavation [35–37]. This technique provides a large blasting power and is considered as physical blasting. The kernel of this technology is the blasting system, which consists of release tube containing release holes, a cutting plate, liquid storage tube containing heating pipe, guide tube and detonator following the order from the top to the bottom. By starting the detonator, special chemicals in the heating pipe begin to react and a lot of heats then are released instantly to heat the liquid carbon dioxide in liquid storage tube. This process brought about the phase change of carbon dioxide and then caused the dramatically expansion of the volume of carbon dioxide. When the pressure of carbon dioxide in the liquid storage tube exceeds the strength of the cutting plate, the cutting plate is damaged and high pressure carbon dioxide enters the release tube and acts on the coal body. No sparks appeared during the blasting process or the transport process, and both the storage and use of the materials were also convenient. By utilizing the phase energy of CO_2 to increase coal body permeability, the energy efficiency can be greatly improved.

2. Liquid carbon dioxide phase change fracturing technology

2.1. Liquid carbon dioxide phase change fracturing system

The liquid carbon dioxide phase change fracturing system contains an above-ground filling system and underground blasting system. As shown in Fig. 1, the above-ground filling system contains an air compressor, CO_2 pump, CO_2 cylinder, etc. Fig. 2 shows that the underground blasting system consists of release tube containing release holes, cutting plate, liquid storage tube containing heating pipe, guide tube and detonator. The heating pipe containing special chemicals connects with guide tube, and the detonator connects with the guide tube by a wire. By using the above-ground filling system, liquid carbon dioxide could be injected into the liquid storage tube. The volume of the liquid storage tube is 1.26 L, and the liquid carbon dioxide contained in the storage tube weighs 1.248 kg–1.4 kg.

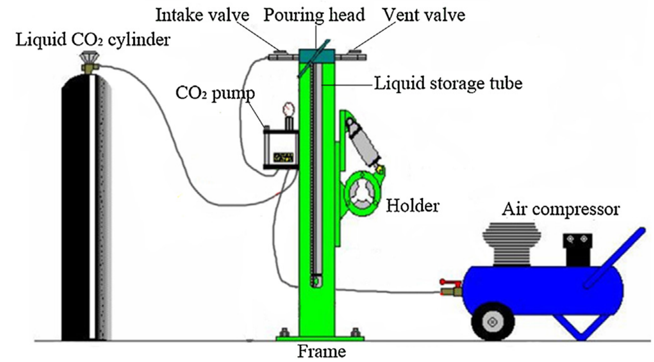

Fig. 1. Above-ground filling system.

The release tube, the liquid storing tube and the guide rod are connected by screws, and the guide rod has a built-in conducting wire that can conduct electricity after being connected. During the testing process, the release tube and the liquid storing tube could be set to a predetermined position by increasing the number of guide rods. Then, by starting the detonator, special chemicals in the heating pipe begin to react and a lot of heats could be released instantly (a few milliseconds) to heat the liquid carbon dioxide in liquid storage tube. This brought about the occurrence of phase change and caused the dramatically expansion of the volume of carbon dioxide. When the pressure of carbon dioxide in the liquid storage tube exceeds the strength of the cutting plate, the cutting plate (seen from Fig. 2) is damaged, and carbon dioxide with high pressure enters the release tube and acts on the coal body. According to laboratory test results, the damage pressure of the cutting plate is approximately 270 MPa. This means the pressure of carbon dioxide acting on the coal body is also approximately 270 MPa.

2.2. Permeability-improvement mechanism of liquid carbon dioxide phase change fracturing technology

Permeability-improvement mechanism of the liquid carbon dioxide phase change fracturing technology is similar to hydraulic fracturing. However, the pressurization methods of two technologies are different. Compared with hydraulic fracturing, the equipment of the liquid carbon dioxide phase change fracturing technology is simpler, the pressure is larger, and the process is also faster. More importantly, it is an effective way of achieving the optimum fracture network.

After the cutting plate is damaged, a shockwave and high-pressure carbon dioxide gas are generated and begin to be released by the release tube and act on the coal body. Under the action of the shockwave, radial compression and tangential stretching is generated around the borehole. When the tangential tensile stress exceeds the tensile strength of the coal body, radial cracks are generated and spread as the shockwave propagates. As energy is lost, the shockwave gradually attenuates. Lastly, when the tangential tensile stress generated by the shockwave is less than the tensile strength of the coal body, the crack stops extending. Additionally, as the shockwave propagates forward, high-pressure carbon dioxide gas immediately follows the shockwave and enters