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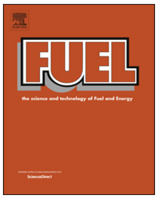

Full Length Article

The correlation between dynamic phenomena of boreholes for outburst prediction and outburst risks during coal roadways driving

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ABSTRACT

Coal and gas outburst accidents occurring in underground coal mines generally cause great casualties and economic losses, especially in construction areas of coal seams where the outburst risks are not accurately evaluated. Therefore, accurately identifying the outburst risks of coal seams is necessary and critical to prevent and control outbursts. In order to improve the prediction accuracy for outbursts in working faces of coal roadways, a self-designed drilling device that can simulate the *in-situ* outburst prediction of coal roadways was used in this study. We used the coal samples with different coal ranks to adsorb CO_2 and N_2 with different pressures in the laboratory, so as to simulate the coal seams with different outburst risks. Finally, boreholes for predicting the outburst risk were drilled in the simulated coal seams to study the correlation between common dynamic phenomena (e.g. gas and coal being ejected from the borehole (GCEB) and drill pipe being stuck by coal mass in the borehole (DPSC)) and outburst risks. The results show that the greater the outburst risks of coal seams, the more frequent the occurrence of GCEB and DPSC is. The GCEB phenomenon for outburst prediction is attributed to small-sized coal and gas outbursts in boreholes, while the occurrence of DPSC phenomenon does not affirm that there definitely are outburst risks on working faces.

The DPSC phenomenon indicating outburst risks is generally accompanied with GCEB, which form a linkage system and are triggered successively.

1. Introduction

Coal is one of the most important energy sources in the world and is the basic energy for China [1]. In coal mining, various accidents, such as coal dust explosion, gas explosion, fire, and coal and gas outburst generally happen [2–5]. In these accidents, coal and gas outburst often causes the most serious damages and produces secondary disasters [6–8]. In China, 25 gas accidents happened in the first three quarters in 2015, resulting in 89 deaths, and the outburst accident accounted for about 30% [9]. For the consideration of economy, environment and safety, many countries in the world have closed coal mines with outburst risks and the United Kingdom even has stopped mining in all coal mines since 2016. However, according to the estimations, more than 2000 coal mines with outburst risks are still in operation across the world [10]. Particularly, in recent years, the mining depth of coals is increasing at an annual rate of 10–20 m, and even the mining depth in some areas reaches 50 m per year [11]. With the increase of mining depth, due to the effects of high *in-situ* stresses and gas pressures, more and more mines originally without outburst risks change into ones with outburst risks, so do coal seams. Therefore, the prevention and control over coal and gas outburst is still a great challenge. In accordance with statistics, coal and gas outburst accidents generally occur on working faces of coal roadways [12,13].

To effectively control coal and gas outburst accidents, accurate outburst prediction is essential and critical [6,11,12,14,15]. At present, many scholars have proposed a lot of methods and indexes for outburst prediction. These methods consist of electromagnetic radiation (EMR) monitoring technology, establishment of mathematical models and division of geological units [11,16–20]. Owing to the method of EMR monitoring technology is disturbed by many factors in applications, the received data are not accurate. As for the mathematical method, to ensure accuracy, a large number of data require to be collected in advance, while newly built mines or mining areas lack of these data [12]. The prediction method of drilling prediction boreholes on working faces is widely used in the world, which measures indexes including gas desorption indexes (k_1, Δh_2 and q) and drilling cutting weight (S) from boreholes [11,21,22]. However, because of human factors or distinct sensitivities to these indexes in different coal mines, different areas with

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outburst risks, resulting in various critical values for outburst, and thereby "low-index outburst accidents" happen [6,12]. Some dynamic phenomena like GCEB, DPSC, DPMA (drill pipe moving forward in the absence of an artificial push) generally occur in drilling and show commonness in boreholes with outburst risks, thus they can be used as the criteria for outburst prediction [23].

According to the four stress areas (stress relieving zone, pre-peak stress concentration zone, post-peak stress concentration zone and original stress zone) formed in front of working faces of coal roadways, Wang et al. [24] established the failure mechanics model for boreholes. Furthermore, by using this model to analyze the evolution of GCEB, they considered that GCEB is most likely to occur in the post-peak stress concentration zone and the faster the drilling speed, the higher the occurrence possibility is. Ou et al. [25] drilled a small hole in front of coal masses in advance by using the developed device for simulating outburst. They knocked the coal masses to realize the sudden exposure of coal, so as to simulate the occurrence of GCEB. Moreover, the evolution characteristics of fractures in coal masses during GCEB process was analyzed. Sun et al. [26] and Wang et al. [27] believed that in the construction of boreholes in strong outburst-prone soft coal seams, the drill enters into 'hole cave'(a local area in the borehole whose diameter is larger than that of the borehole), thus leading to DPSC accidents. Furthermore, based on the movement laws of drillings, Zhang et al. [28] analyzed reasons for DPSC and DPMA and held that too fast drilling speed in soft coal seams with outburst risks can result in the occurrence of the two phenomena. From the coupling perspective of stresses and gas pressures of coal masses, Fernandez-Diaz et al. [29] studied the factors influencing gas dynamic phenomena in the tunneling of coal roadways. Nevertheless, most of the above studies mainly describe the reasons for the occurrence of dynamic phenomena including GCEB and DPSC. While the relationship of these phenomena with outburst risks, especially the characteristics the DPSC with and without outburst risks, as well as the correlations of dynamic phenomena during drilling are rarely investigated. In addition, similar reports on drilling for outburst prediction in coal roadways simulated in laboratories are seldom found. By utilizing a set of self-designed drilling devices that can simulate the *in-situ* outburst prediction of coal roadways, the coal seams with distinct outburst risks were simulated by using the coal samples with different ranks to adsorb CO_2 and N_2 with different pressures. Furthermore, in the experiment, stress sensors were placed in the simulated coal seams. Finally, based on drilling boreholes for outburst prediction, this study investigated the correlations of the common dynamic phenomena including GCEB and DPSC with outburst risks, as well as the correlations of these phenomena.

2. Experimental

2.1. Experimental equipments

Dynamic phenomena including GCEB and DPSC occur in the drilling boreholes for outburst prediction in normal tunneling of underground coal roadways. For this reason, in order to normally simulate these phenomena in the laboratory and coincide with the conditions of conventional construction on site, the simulated coal seams with different outburst risks were selected in which boreholes for outburst prediction were drilled. In normal drilling, the relationship between these phenomena and outburst risks of simulated coal seams were analyzed, as well as the relationships of these dynamic phenomena. A uniaxial loading machine with the maximum applied force of 10,000 kN was utilized as the pressurization system in this experiment and the equipment for simulating coal seams was an oblong cylinder of 1120 mm, 220 mm and 330 mm in length, width and depth, respectively. Through the calculation, the upper surface area was 0.235994 m^2. Therefore, when the loading machine reached the maximum applied force, the briquetting pressure of coal seams was 42.37 MPa. The whole experimental system is shown in Fig. 1.

2.2. Coal samples

Outburst disasters mainly occur in tectonic coals with various characteristics including low mechanical strength, strong gas adsorption capacity, and rapid desorption of gases after failures [30–33]. Owing to the tectonic coal being regionally distributed [16,32,34,35], and the experiment requiring large amounts of coal samples, it is difficult to collect enough tectonic coal samples on site. The coal samples collected in the study were all non-tectonic coal from corresponding coal seams in various coal mines. Research showed that the briquette coals obtained by crushing non-tectonic coal blocks into coal particles of a certain particle size on which corresponding stresses were imposed exhibited similar mechanical strength, adsorption, and desorption of gases to those of the field tectonic coal masses [32,36,37]. In addition, the tendency of outburst risks of coal seams has certain relations with coal types [30,31,38]. In this experiment, four coal samples with different coal ranks were used. The specific locations where the coal samples were collected are demonstrated in Fig. 2 and the basic parameters refer to Table 1. Each coal sample was pressed into briquette coals for eight times. N_2 and CO_2 were used to simulate the gases adsorbed onto coal seams in this experiment. This is because CH_4 has the explosion risks in the experiment, but showing similar adsorption characteristics with CO_2 and N_2 on the surfaces of coal masses: the adsorption ability ratio of N_2, CH_4 and CO_2 on pore surfaces in coal masses is about 1:2.5:5 [39]. Each coal sample was used to simulate coal seams adsorbing CO_2 and N_2 for four times separately and the simulation experiments were conducted for 32 times in total.

2.3. Experimental processes

2.3.1. Crushing raw coals to pulverized coals

After the raw coals were taken from coal mines and transported into the laboratory, the coal samples were crushed and screened to obtain coal samples with sizes less than 2 mm. After adding a proper amount of water, the coal samples were stirred sufficiently, and finally sealed.

2.3.2. Pressing the pulverized coals into briquette coals

When pressing briquette coals, 30 MPa stresses were applied. In order to compress coal samples sufficiently, the pressing process was conducted in five times each of which lasted for 30 min to press 45-mm-thick coal seams.

2.3.3. Vacuumizing and gas supplying

After the briquette coals were pressed, the coals were vacuumized for no less than 12 h. For the sake of safety, CO_2 with a stronger adsorption capacity and N_2 with a weaker adsorption capacity than CH_4 were pumped into the coal samples in the experiment. Moreover, to ensure gas adsorption equilibrium, the gases were pumped in for more than 48 h. Gas was supplied at the same time of loading *in situ* stress and the latter was gradually increased to the pre-set value. If the *in situ* stress is applied in the early stage when coal seams had not finished gas adsorption, it is unfavorable for gas transfer in coal seams, which increased time for gas adsorption equilibrium. Therefore, the pressing was carried out in three times. Firstly, 100–400 kN were loaded. The second pressing was loaded to the half of pre-set value of *in situ* stress, and then the stress was increased to 20 MPa, the pre-set *in situ* stress. The three loadings should be finished within 36 h after the beginning of air supply and held for at least 12 h to observe whether reached the gas adsorption equilibrium.

2.3.4. Drilling for measuring parameters

In order to guarantee that sufficient gases had been adsorbed on the simulated coal seams and it had reached adsorption equilibrium in drilling, the pressure gauge reading needed to be unchanged during at least 2 h before opening the plug. Furthermore, due to low strength of the pressed briquette coals, to prevent serious deformation of boreholes