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Short communication

Risk analysis of coal self-ignition in longwall gob: A modeling study on three-dimensional hazard zones

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ABSTRACT

Coal self-ignition in longwall gob (mined-out) areas has caused serious personal casualties and economic losses. Effective determination of coal self-ignition hazard zones in longwall gob areas can enable more targeted fire prevention. In this paper, the effects of ventilation mode and working face dip on the oxygen supply for coal self-ignition were studied. A three-dimensional dip-adjustable physical model of the longwall gob was developed to study the coal self-ignition hazard zones at different dip angles varying from $-45°$ to $+45°$ with respect to the horizontal plane. In addition, the coal self-ignition risk was analyzed through the position, width and space range of the hazard zones. The results demonstrate that the hazard zone features "***S***"-types both in the dip and the advanced directions of the working face, with a dip angle ranging from $+5°$ to $+15°$ the hazard zone primarily locates on the lower air intake side close to the middle when the angle exceeds $+25°$. With an angle ranging from $-5°$ to $-45°$, the hazard zone scope is reduced along the direction from the upper side to the lower side and gradually concentrates at the lower air return side. Being different from the probability of coal self-ignition, the hazard severity may reduce with dip angle regardless of ventilation mode. A risk analysis method based on three-dimensional physical modeling is proposed and applied to analyze the coal self-ignition in the longwall gob. This analysis is of great significance for both fire safety and miners' health.

1. Introduction

Longwall mining is a continuous process in an extensive area, where a mechanical shearer progressively mines a large block of coal called a coal seam. Above the coal seam, the formation layers fracture and separate as a result of the stress release caused by immediate roof strata caving, forming a fractured zone called a "gob" [1,2]. Self-ignition generally occurs in gobs that are not accessible [3]. In China state-owned collieries, coal self-ignition fires, 60% of which occur in gob areas, account for 90–94% of all mine fires [4]. Air leakage from the working face to the gob area provides piled up coal with an oxidizing environment, which makes the heat generated by oxidation easily accumulate, leading to an increased temperature. Sufficient oxygen and accumulating heat can easily cause coal self-ignition [5] which leads to significant economic losses, personal casualties, and environmental pollution [6–8]. Therefore, risk analysis for coal self-ignition in longwall gob areas is imperative to reduce the environmental pollution potentials and to promote sustainable development of coal resources. The risk analysis has been carried out by many methods. The susceptibility of coal self-ignition is the key issue. It has been ranked by adopting different laboratory methods, such as the adiabatic oxidation method, activation energy method, heat release method, ignition temperatures method, crossing point temperature (CPT) method, and so on [9]. However, these studies mainly focus on the performance characteristics of coal self-ignition. Few are focused on the impact of mining conditions on coal self-ignition.

The distribution of oxygen concentrations is the key factor to the risk assessment of coal self-ignition and fire prevention [10]. The whole longwall gob area can be divided into three zones based on the oxygen concentration: the no-self-ignition zone where the oxygen concentrations are more than 18%, the self-ignition zone where the oxygen concentrations are between 10% and 18%, and the suffocation zone where the oxygen concentrations are less than 10% [11–13]. The oxygen concentrations are high in the no-self-ignition zone because of larger amount of air leakage. The air leakage removes the heat from the coal oxidation and makes it

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difficult for temperature accumulation and the occurrence of self-ignition. The low oxygen concentrations in the suffocation zone inhibit coal oxidation. In the self-ignition zone, the coal oxidation produced heat is greater than the heat removed by the air leakage, thus accumulating heat and causing coal self-ignition. Hence, the self-ignition zone is regarded as the hazard zone. Following two external conditions are usually used to determine the self-ignition zone in the gob area: 1) coal oxidation occurs and its heat will be accumulated (vol. $O_2 < 18\%$), and 2) there is sufficient oxygen (vol. $O_2 > 10\%$).

Air leakage is the essential cause of the uneven distribution of the oxygen concentrations in the longwall gob area. Song et al. [14] developed a two-dimensional unsteady-state model for hill-side coal fires. They analyzed the influences of air leakage on abandoned galleries in hill-side coal fires. Hu et al. [15] analyzed the air leakage characteristics in the gob under stereo gas extraction conditions. Their study did not consider the diffusion characteristics of air leakage through porous media in the longwall gob area. The ventilation and the advancing speed of the working face have a direct impact on coal self-ignition in the longwall gob area and have recently been investigated by many researchers [16–18]. For example, a fully coupled hydro-thermo- mechanical model has been proposed to reveal the self-heating process of underground coal seams [19,20]. This model considers the complex interactions among geomechanical deformation, oxygen transport and flow, and energy transport. Because of the complexity of the self-ignition process and the difficulty of field measurements in caved rocks, most studies are mainly based on numerical simulations in two-dimensional space. The spatial accumulation pattern of coal oxidation in the gob area is important to the heat accumulation, thus the hazard zones should be determined in three-dimensional space.

Steep coal seam mining has become a focus right now because of the decline in coal resources exploitation. The feasibility analysis of steeply inclined working faces in gobs has been explored [21]. However, less attention has been paid to coal seam dips. The dip effect was studied in an inclined tunnel fire with dip angles variable from $-10°$ to $10°$ with respect to the horizontal plane. The negative correlation with CO concentration and the positive correlation with both the smoke layer thickness and the smoke outflow rate were revealed [22]. These correlations made sense to the prevention of mine fire in the gob area. Numerical calculations and field observations of roof movement and support stability in inclined coal seams were also performed [23].

Mining of inclined coal seams usually uses two ventilation modes: ascensional ventilation, which is defined as air flowing from the bottom up along the inclined direction of the working face, and descensional ventilation that is the opposite of ascensional ventilation [24]. For horizontal coal seams, the airflow direction is horizontal, being neither ascensional ventilation nor descensional ventilation. Such airflow ventilation is called horizontal ventilation. Different ventilation modes should be considered for study completeness. In this paper, an experimental simulation model based on the morphological characteristics of a conventional longwall gob was built. It will be used to measure the distribution of oxygen concentrations under different dip angles and in different ventilation modes in the three-dimensional self-ignition zone. It is expected to analyze the risk and hazard zones of coal self-ignition in longwall gob areas from all directions.

2. Materials and methods

2.1. Experimental setup of three-dimensional dip-adjustable longwall gob

The dip-adjustable three-dimensional model is shown in Fig. 1. This is a model with a scaled down to 1:50 ratio from a conventional longwall gob. Table 1 lists the basic parameters for the actual and simulated values. This model is 3 m in length, 1.8 m in width and 1 m in height. The porosity is decreased because of the overlying strata re-compaction at the 150-m depth of the longwall gob area where the oxygen concentration is less than 10% [11,17] and in the suffocation zone. The gob created by longwall mining can reach 4–11 times the thickness of the mining height. In this gob, overburden rocks were weak and porous [25]. The model height is taken as 16 times the mining height. Such a height can provide sufficient space for gob design. Both the air intake roadway and the air return roadway are 1 m in length, 0.1 m in width and 0.06 m in height. The material in the gob is highly fragmented and broken into irregular shapes of various sizes. The gob can contain high void ratios because of fragmented rock pieces. Thus the gob can be regarded as a completely fragmented porous medium [25]. The porosity of the gob was set to decrease linearly in the vertical direction from the value of 25% at the floor to 5% on top of the gob. Its permeability is the largest around the perimeter of the gob and immediately decreases in the center [16]. According to field observations of the working face, the sizes of the caved rocks are approximately 0.25–2.5 m and gradually increase with the height from the floor because of the decreasing fractured degree of the rocks. Considering the load-bearing of the model, it is hard to adjust the dip angle if the simulated gob is filled with some original materials (rocks). The foam blocks can be used to fill the gob. The blocks are foam plastics with numerous micropores inside and can be fabricated into irregular shapes. They can be also assembled to form a fragmented porous medium. Such foam blocks can be well applied to simulate bulk coal refuse block piles [26]. In the experiment simulation model, the caved zone and fractured zone in the longwall gob area are simulated by filling different foam blocks to mimic the above situation. The caved zone is filled with 5–100 mm irregularly shaped foam blocks. The fractured zone is filled with 100–300 mm irregularly shaped foam blocks. At the same time, the foam blocks in the center of the gob are compacted to a certain extent to make the permeability lower than that around the perimeter of the gob. The longwall gob is airtight apart from the openings of the air intake and return roadways.

A low-oxygen environment in the longwall gob area was created through the nitrogen in a cylinder. A gas flowmeter with a measurement range of 0–20 L/min can monitor air flow of 7.2 L/min. According to the requirements of the experiment, a FY-1H-N miniature vacuum pump is applied to achieve negative-pressure ventilation with a rate of 3.6 m^3/h. The rotating mechanism includes a turbine worm reducer. It uses a gear speed converter to decelerate the rotation to the required value if more torque is expected. The dip angle can be adjusted from $-50°$ to $50°$ by the rotating mechanism. Both ascensional and descensional ventilations can be obtained by inversing inclined direction of the model.

Further, electrochemical oxygen sensors (4OXV) with a measurement range of 0–25 vol%, a zero current (offset) of less than 0.6 vol% and a response time of less than 15 seconds are applied to monitor oxygen concentration values in real-time in order. The values at different measurement points can be displayed on the screen of computer. Twenty-four measurement points with serial numbers are shown in Fig. 2. These points are arranged in three sections perpendicular to both the working face and the baseplate. Sections A, B and C are located on the air intake, middle and air return side, respectively, in the longwall gob area. The distance from the air intake roadway side to Sections A, B and C are 0.3 m, 0.9 m, and 1.5 m, respectively. Eight measurement points in each section are arranged on three floors that are 0.06 m, 0.15 m and 0.24 m away from the baseplate, respectively. Because the overlying strata upon the coal seam cannot self-ignite, the upper floor