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Risk analysis of spontaneous coal combustion in steeply inclined longwall gobs using a scaled-down experimental set-up

Su Hetao[a,b], *Zhou Fubao*[a,b,c,*], *Song Xiaolin*[a], *Qiang Ziying*[a,b]

[a] *Key Laboratory of Coal Methane and Fire Control, Ministry of Education, China University of Mining and Technology, Xuzhou 221116, China*

[b] *School of Safety Engineering, China University of Mining and Technology, Xuzhou 221116, China*

[c] *State Key Laboratory of Coal Resources and Mine Safety, China University of Mining and Technology, Xuzhou 221116, China*

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ABSTRACT

Spontaneous coal combustion in longwall gobs which are formed via underground mining is responsible for the loss of coal resources and impairs the ecological environment. Few studies are focused on risk analysis of spontaneous coal combustion in steeply inclined longwall gobs with experiments. In this work, an inclination-adjustable longwall gob model was developed to analyze the effects of airflow direction and ventilation rate on the oxygen concentration in steeply inclined longwall gobs (inclination angles of $\pm 55^{\circ}$). According to the oxygen concentration gradients, the Spontaneous Coal Combustion Risk Zone (SCCRZ) was drawn. Furthermore, a simple practical method was proposed to quantitatively determine the risk of spontaneous coal combustion in steeply inclined longwall gobs. The results show that the SCCRZ mainly focuses on the lower side regardless of airflow direction. When the working face airflow direction is from the lower side to the upper side, the risk of spontaneous coal combustion tends to be stable with increasing ventilation rate. In case of the opposite airflow direction, the risk of spontaneous coal combustion increases significantly with increasing ventilation rate.

1. Introduction

Most coal mine fires are caused by spontaneous coal combustion, which generally occurs in longwall gobs that are not accessible (Chi, 2008; Deng et al., 2013; Taraba and Michalec, 2011; Qi et al., 2015). In the process of coal mining, because fresh air in the working face flows continuously to the gob where there is residual coal, the residual coal is provided with sufficient oxygen to oxidize and spontaneously combust. As a result, it can produce large amounts of toxic and harmful gases, threaten the safety of miners, and cause serious economic losses and environmental damage (Ray and Singh, 2007; Kim and Sohn, 2012; Querol et al., 2011; Wang et al., 2003; Dudzińska and Cygankiewicz, 2015). To predict the likelihood and severity of spontaneous coal combustion and determine the Spontaneous Coal Combustion Risk Zone (SCCRZ), risk analysis of spontaneous coal combustion in longwall gobs is important to identify ways to prevent coal mine fires efficiently.

Currently, the susceptibility of coal self-ignition has been ranked by using different laboratory methods to assess the risk of spontaneous coal combustion. These laboratory methods include the ignition temperature method, the adiabatic oxidation method, the activation energy method, the heat release

* *Corresponding author at*: School of Safety Engineering, China University of Mining and Technology, Xuzhou 221116, China. Fax: +86 516 83995053.
E-mail address: f.zhou@cumt.edu.cn (F. Zhou).

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method and the crossing point temperature (CPT) method (Qi et al., 2015; Pandey et al., 2012). Given that coal oxidation at low temperature provides a major source of heat for coal self-heating and spontaneous combustion, many scholars have carried out coal low-temperature oxidation experiments to study the reaction kinetics (Kim et al., 2015; Zhang et al., 2015; Arisoy and Beamish, 2015). These studies focused on the internal factors of spontaneous coal combustion, namely coal ignitability, but external factors might be ignored, such as airflow direction and inclination angle of the gob as discussed by Su et al. (2016) and ventilation volume and rate. Otherwise, analytic hierarchy process (AHP), neural network and fuzzy c-means clustering approaches were applied to analyze the risk (Song et al., 2014; Panigrahi and Sahu, 2004; Sahu et al., 2011, 2012). Some numerical simulations were conducted based on different (plane, spatial or hydro-thermo-mechanical) mathematical models to analyze coal self-heating processes and to predict the risk of spontaneous coal combustion. Taraba and Michalec (2011) established a spatial single-phase model to understand the oxidation heat production and the evolution of the gases in the gob area in the case of a continuously advancing working face. Based on geological processes combined with compositional gas transport and energy transport, Xia et al. (2014, 2015) developed fully coupled models to quantitatively predict the coal self-heating zones underground. As mentioned above, little attention was paid aiding risk analysis using experiments.

With the decline in available coal resources there is a pressing need to exploit the steeper coal seams (Deng and Wang, 2014). The residual coal on the upper side of the steeply inclined longwall gob can accumulate on the lower side due to its own gravity, while fresh air leaks into the gob. Thus, the residual coal is provided an external circumstance for oxidation and heat accumulation. However, little research has been reported to analyze the risk of spontaneous coal combustion in the steeply inclined longwall gob. Oxygen is the key factor for spontaneous coal combustion. Polish scholars initially utilized oxygen consumption to indicate spontaneous coal combustion based on the certain correspondence between the oxygen consumption rate and the state of spontaneous coal combustion (Wang, 2008). Akgün and Arisoy (1994) analyzed the effect of particle size on the oxidation rate in greater depth according to the oxygen consumption and the temperature of the coal bed. The oxygen consumption rate of the coal, as well as the nature and quantity of gaseous products were studied to qualitatively determine the different reactions occurring in coal (Wang et al., 2003; Deng et al., 2015, 2016; Xu et al., 2017). Furthermore, numerical studies on spontaneous coal combustion have become a trend, where the oxygen consumption rate is one of the necessary parameters (Taraba and Michalec, 2011; Wang et al., 2013; Xia et al., 2014). According to the oxygen concentration gradients, the intensity of air leakage, and/or temperature variation in longwall gobs, the working face was divided into three zones (no self-ignition zone, self-ignition zone and suffocation zone) by researchers in Poland (Deng et al., 2013; Pan et al., 2013). The division method based on the oxygen concentration was simple and practical, and was widely used to predict the SCCRZ. It was defined that the no self-ignition zone was where the volume fraction of oxygen is more than 18%, the self-ignition zone where the volume fraction of oxygen is between 10% and 18%, and the suffocation zone has volume fractions of oxygen less than 10% (Su et al., 2016; Di and Liu, 1993; Jiang and Zhang, 1998; Wu et al., 2011). The volume fraction of oxygen of more than 18% in the no self-ignition zone was the result of abundant air leakage. The heat from coal oxidation could be removed by the air leakage, making spontaneous coal combustion difficult. The coal oxidation was inhibited with volume fractions of oxygen less than 10% in the suffocation zone. In the self-ignition zone, the heat from coal oxidation was not completely taken away by air leakage, and the accumulating heat would cause spontaneous coal combustion. Hence, the self-ignition zone could be regarded as the SCCR. Xu et al. (2002) presented a relationship between the risk of spontaneous coal combustion, coal ignitability, working face advancing speed and SCCRZ. At the same time, a simple risk assessment of spontaneous coal combustion was proposed. When the risk existed, the relationship could be expressed by Eq. (1).

$$\tau = \frac{L_{\max}}{v(t)} \geq \tau_{\min} \tag{1}$$

where $L_{\max}$ was the maximum width of the SCCRZ along the working face advancing direction in meters, $v(t)$ was the working face advancing speed (meter/day), τ was the longest time that the residual coal stayed in the SCCRZ (day), and $\tau_{\min}$ was the shortest coal self-ignition period in air through laboratory testing (day). $L_{\max}$ and $\tau_{\min}$ represented the characteristic of the SCCRZ and the coal ignitability respectively. Eq. (1) shows that there is a risk of spontaneous coal combustion in longwall gobs, when the longest time that the residual coal stays in the SCCRZ, is greater than the shortest coal self-ignition period. The oxygen concentration in the gob is uneven and less than the oxygen concentration in fresh air. Besides, the oxygen concentration decreases gradually with distance from the working face, while $\tau_{\min}$ is obtained by testing in fresh air. Therefore, the risk of spontaneous coal combustion as determined by Eq. (1) is greater than the actual risk.

Cliff et al. (2000) constructed a large scale (16 m^3) reactor to allow coal to self-heat under conditions similar to that found in gobs, and the temperature and gaseous products were obtained and analyzed. Deng et al. (2015) conducted a large-scale spontaneous combustion tests by using a 15-tonne experimental furnace, and the temperature variation, oxygen consumption rate, heat intensity and gas ratios were analyzed for the evaluation of fire risk assessments. Su et al. (2016) study the hazard zones of spontaneous coal combustion at different inclination angles by using a three-dimensional dip-adjustable physical model of a longwall gob. Given that there is little research at present on the relevant risk analysis using experiments for the spontaneous combustion of residual coal in steeply inclined longwall gobs, an experimental study on the risk of spontaneous coal combustion in a steeply inclined longwall gob was executed, and the effects of external factors (steeply inclined coal seam, ventilation volume and rate and airflow direction) on the distribution of the oxygen concentration in the gob were analyzed to determine the distribution regularity of the SCCRZ. Furthermore, an effective method for risk analysis was put forward in order to provide an important experimental basis for the prevention of spontaneous coal combustion in steeply inclined longwall gobs.

2. Materials and methods

2.1. *Experimental setup*

An inclination-adjustable longwall gob model was developed on a 1:50 scale corresponding to the conventional gob. The