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Unique spatial methane distribution caused by spontaneous coal combustion in coal mine goafs: An experimental study

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ABSTRACT

A new type of incident in the form of a methane explosion caused by spontaneous combustion of coal is receiving more and more attention due to the high ground temperature and high methane content in coal mines. To investigate the formation process of this type of incidents and advance the research on methane explosion risk caused by spontaneous coal combustion, a self-designed experimental platform was used to determine the influence of spontaneous coal combustion on methane migration in the goaf. Additionally, the effect of different ventilation velocities at the mining face on methane migration in the goaf was studied. The results reveal that air leakage plays a key role in methane migration in the goaf. The bigger the ventilation velocity, the larger the area affected by air leakage. In addition, the superposition of the air leakage and the horizontal and vertical movement of hot gases creates the entrainment effect in the spontaneous combustion area. Eventually, the methane concentration at the location of spontaneous combustion is the lowest and it gradually increases outside the spontaneous combustion area because of the superposition of air leakage, 'fire pressure' and the entrainment effect.

1. Introduction

Coal is one of the most important energy resources in the world. Most coal mines in China are underground coal mines with complicated coalbed storage conditions, which have risk factors, such as spontaneous coal combustion, coal dust explosions and/or methane explosions. Among the risk factors, the potential occurrence of both spontaneous coal combustion and a methane explosion is a serious engineering problem. In China, accidents involving spontaneous combustion of coal occur more often than before because of the application and popularization of fully-mechanized caving mining methods that will leave more coal in the goaf (Wang et al., 2010). Spontaneous coal combustion will occur when there is enough oxygen for coal oxidation and a suitable heat build-up. The mine goaf, caving zone of the roadway and the so-called stopping mining line are the places where this phenomenon is most frequently occurring. Many theoretical and experimental approaches are used to investigate the different kinds of spontaneous combustion under various conditions (Boleslav and Zdeněk, 2011; Xia et al., 2014; Yuan and Smith, 2012; Wu et al., 2014; Wang et al., 2009; Cheng et al., 2017). Some typical sensitivity indexes and methods based on coal sample experiments or engineering experience can be used to assess the possibility of spontaneous combustion and its spontaneous combustion stages (Xie et al., 2011; Xie, 2012; Singh et al., 2007; van Dijk et al., 2011; Li et al., 2014; Nimaje and Tripathy, 2016; Avila et al., 2014; Ren and Balusu, 2009; Kong et al., 2017). To achieve conditions close to the actual spontaneous combustion conditions, researchers have built experimental models, such as coal stockpiles and big experimental ovens, to simulate the spontaneous combustion under different experimental conditions to elucidate the physics behind these phenomena (Smith and Glasser, 2005; Hooman and Maas, 2014; Taraba et al., 2014).

Methane release poses serious explosion hazards in the coal mining industry and creates greenhouse gas emission issues. The common forms of methane accidents in mines involve methane outbursts, coal and methane outbursts and coal-rock-methane outbursts (Wen et al., 2017). Methane drainage and methane utilization technologies, rapidly developed in recent years, are effective approaches to avoid possible methane explosions (Kissell, 2006; Karacan et al., 2011; Qin et al., 2017). Nevertheless, spontaneous coal combustion in a goaf may lead to the closure of the goaf and the methane migrating in the goaf may be ignited which could lead to gas explosions (Shi et al., 2017; Huang et al., 2017; Cao and Li,

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Table 1
Experimental platform size.

Part	Length/cm	Width/cm	Height/cm
Roadway	20	4	3
Mining face	120	5	3
Coal mine goaf	200	120	80

2017). Researchers have studied the explosion limits and explosion characteristics of methane, such as explosion pressure and rate of pressure rise (Oh et al., 2000; Pekalski et al., 2000; Cheng et al., 2012, Cheng and Yang, 2011). However, due to the complex engineering and geological conditions, the development of methane explosions in coal mines requires more detailed study (Qin et al., 2016; Zhou et al., 2008; Dubaniewicz, 2009).

A coal mine goaf is a potentially dangerous area where large amounts of methane migrates and accumulates and spontaneous combustion may occur (Xia et al., 2015; Hu et al., 2017; Rubtsov et al., 2008). The environment in coal mines, such as the high ground temperature and the high methane content, make it possible that both spontaneous coal combustion and a methane explosion may occur simultaneously. Research on this combined accident is limited and the availabe information is focused on the numerical simulation of the phenomenon. A coupled model was made to simulate the coal self-heating processes in methane-rich coal mines (Xia et al., 2015, 2016). The numerical simulation results indicate that methane drainage can increase the risk of spontaneous coal combustion in the goaf (Li et al., 2007; Zhu et al., 2011; Qin et al., 2016). However, there is no experimental validation of these simulations. In this study, a self-designed experimental platform was used to research methane migration and its distribution under the influence of spontaneous coal combustion, which is important for taking reasonable measures to prevent this type of accident.

2. Experimental setup

2.1. Experimental platform

The experimental platform was built to simulate the conditions in Xing'an coal mine located in Hegang, Heilongjiang province, China (Jiao et al., 2012). In the accident that happened in the Xing'an coal mine, there were 7 methane explosions caused by spontaneous combustion while measures were taken to mitigate the explosions in the first place. The mining face is about 120 m long, 5 m wide and 3.5 m high, while the air inlet roadway and air return roadway have the same size, which is about 650 m long, 4 m wide and 3 m high.

The experimental platform was one hundredth of the size of the original coal mine and the dimensions of the experimental platform are given in Table 1. Since the density and viscosity of air change little in both situations, the ratio of the velocities between the simulation platform and the actual mine is the square root of the ratio of the lengths between the simulation platform and the mine. The ventilation velocity is a variable, which is used to test its effect on the prevention of the methane explosion. In actual mines, the ventilation velocity should be between the minimum value of 0.25 m/s and the maximum value of 4 m/s in the mining face. For the coupling of spontaneous coal combustion and methane explosions, increasing the ventilation volume is an important measure to control the environment in the mine. Thus, three mining face velocities (0.2, 0.6 and 1.0 m/s) were adopted in this research. The experimental platform, shown in Fig. 1, contains a ventilation device, a volume representing the goaf, a methane releasing device and a temperature monitoring device. The methane concentration is measured by a helium concentration detector and silica gel tubules. The tubules are buried in the goaf and the suction port is located at the monitoring point (Fig. 3) while the other port is outside the goaf to connect the helium concentration detector. Through monitoring changes in temperature and methane concentration in the goaf with time, the dynamic change in methane concentration and temperature can be measured.

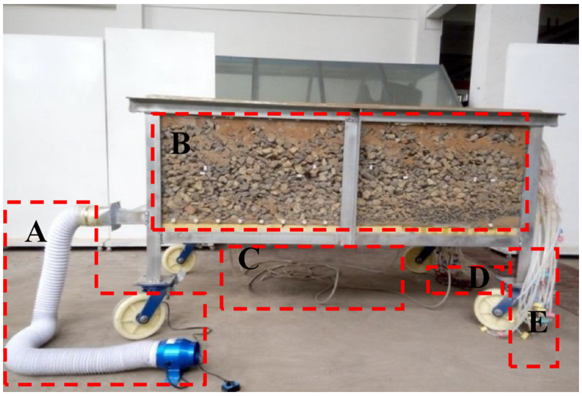

Fig. 1. Simulation platform of methane migration in the coal mine goaf. (A: ventilation device; B coal mine goaf; C: gas releasing device; D: temperature monitoring device; E: data collection device).

2.2. Caving characteristics in the goaf

The coal mine goaf is the room that is filled with caving rock and residual coal, and this environment changes little during the mining period. Through the caving rock and residual coal air can flow into the goaf, also referred to as air leakage.

When coal is mined out, there will be an empty space left, namely the goaf. Due to the gravity, the overlying rock may collapse and fill the goaf. The goaf boundary may consist of coal seam or the rock strata and they are not destroyed by mining. Due to the support of the goaf boundary, the caving rock nearby the boundary is bigger in size and loose while the caving rock in the central area is smaller in size and compacted (Fig. 2a). As a result, the porosity distribution in the goaf has the shape of the letter 'O'. Since the porosity distribution in the goaf is symmetrical, half of porosity distribution is shown in Fig. 2. The porosity in the goaf has a close relationship with the rock bulking coefficient which is the ratio of the volume of a loose broken rock to the volume of the integral original rock. From the top view, the distribution function of the bulking coefficient relative to a specified boundary at a single direction for a given goaf is expressed as (Li et al., 2012):

$$K_p(x,y) = K_{p,\min} + \left(K_{p,\max} - K_{p,\min}\right) \times \exp\left(-a_1 d_1 \left(1 - e^{-\xi_1 a_0 d_0}\right)\right) \quad \left(\xi_1 < 1\right) \tag{1}$$

where, $K_p(x,y)$ is the bulking coefficient, $K_{p,\min}$ is the value of the bulking coefficient of compaction, $K_{p,\max}$ is the initial value of the bulking coefficient, namely the bulking coefficient when the goaf is filled by the caving rock, a_1 is the attenuation rate of the distance to the mining face, d_1 is the distance to the mining face, ξ_1 is the adjustment coefficient, a constant controlling the distribution shape, a_0 is the attenuation rate of the distance to the wall and d_0 is the distance to the wall (Li et al., 2012).

The corresponding caving porosity in the goaf is expressed as:

$$\gamma = 1 - \frac{1}{K_p} \tag{2}$$

where, γ is the caving porosity.

From the sectional view, the overlying layers in the goaf can be divided into three zones, namely the caving zone where the crushed