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Surface-based radon detection to identify spontaneous combustion areas in small abandoned coal mine gobs: Case study of a small coal mine in China

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ABSTRACT

In China, small coal mines refer to non-state-run coal mines with an annual production of less than 300,000 tons. The mining recovery rate of these small Chinese coal mines is low, and large amounts of coal remain in the gob. The mining seams of small coal mines are shallow, which induces extensive fissures between the gob and ground and provides easy pathways for air leakage. Consequently, long-term air leakage and oxygen supplies can result in spontaneous coal combustion in the gob, forming fire areas for many years. Determination of spontaneous combustion areas in the gob of small coal mines is difficult because fire sources are hidden underground and the geological data and roadway layout are poorly documented. Surface-based radon detection provides a fast, accurate, and low-cost method to identify spontaneous combustion areas in the gob of small coal mines. This study focuses on a small abandoned coal mine in Shanxi Province, China, using surface-based radon detection. Three abnormal temperature areas (A, B, C) and a potential abnormal temperature area (D) were identified. Drilling was subsequently performed to measure the temperature distribution in these areas. The results show that spontaneous combustion areas in small abandoned coal mine gobs can be successfully identified.

1. Introduction

Coal is a non-renewable resource and one of the world's most important energy sources (Bloch et al., 2015; Ramola et al., 2008; Squalli, 2017). By the end of 2015, there were more than 9000 coal mines in China with a total annual coal output of about 3.68 billion tons. Alongside increasing production, the amount of coal loss caused by spontaneous combustion also increases annually (Song and Kuenzer, 2014). Fifty-six coalfield fire zones in China have been identified, covering a total area of 720 km^2, located mainly in the arid and semi-arid regions of northern China and concentrated in seven provinces (Xinjiang, Ningxia, Inner Mongolia, Gansu, Qinghai, Shaanxi, and Shanxi) (Kuenzer and Stracher, 2012; Liang et al., 2016; Zhang et al., 2008). Among these fire zones, spontaneous fires in small coal mines account for more than 90% of exogenous fires.

Shanxi is an important province of coal natural resources in China. Its explored coal reserves are about 297 billion tons, making up 17.3% of China's total coal resources. In the 1980s, the number of small coal mines in Shanxi Province exceeded 10,000 due to national policies and economic development needs. While generating economic growth, extensive mining operation in small mines has caused tremendous damage to the ecological environment. Coal resources loss, geological disasters, environmental pollution, and ecological damage caused by mining amounted to at least 5 billion dollars each year (Li, 2011). By the end of 2011, the number of coal mines in Shanxi Province had decreased to 1053 and all small coal mines were shut down. However, negative impacts of small coal mining continue to affect the local area.

The mining recovery rate of small coal mines is generally less than 20%, and large amounts of coal remain in the gob. Moreover, owing to the shallow mining seams of small coal mines and smaller thickness and weaker strength of overlying rock strata, it is difficult to form a caved zone, fractured zone, and continuous zone from the bottom up in the gob to alleviate surface subsidence, as is typical in deep buried coal seams (Jiang et al., 2011). The rock strata above the gob of small coal mines may collapse directly when unable to bear the weight of the upper overburden layer, which causes obvious surface subsidence and creates a substantial amount of cracks and fissures (Wu et al., 2015). As a result, a large number of produced cracks or fissures become pathways for air leakage between

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the gob and surface, all of which can pose a serious danger for the spontaneous combustion of coal (Andrews-Speed et al., 2003; Shen and Andrews-Speed, 2001; Wang, 2007). Safety pillars of a certain thickness are also installed, typically at the mine boundary, which act as insulation and load-bearing walls that can bear the weight of overlying strata, and effectively alleviate damage caused by underground pressure on roadways. However, once spontaneous combustion occurs in the gob of a small coal mine, toxic and harmful gases may enter the working area of larger mines though coal safety pillar fractures, which can directly threatens mining and human safety (Finkelman, 2004; Kuenzer et al., 2007; Liang et al., 2014; Querol et al., 2011).

Spontaneous combustion fires usually occur several hundred meters underground such that fire sources are hidden, which prevents workers from approaching the fire areas. Moreover, because most small coal mines have been abandoned for long periods of time, the geological data are incomplete and roadway excavation procedures are largely unclear, which severely complicate the determination of a fire source location and range within the gob. Currently, fire source detection technology can be summarized as follows: (a) Drilling method. This approach is used to determine the fire source location by analyzing the temperature distribution at different heights in the borehole, and gas composition at the bottom of the borehole. This method is highly reliable with low external interference. However, operation costs are high (Song and Kuenzer, 2014; Stracher and Taylor, 2004). (b) Remote sensing method. This approach is used to initially identify the extent of a coal field fire area and make an early prediction of coal fire. For example, temperature and heat are transferred to the surface when there is a coal field fire in the shallow part of a localized layer. As a result, surface vegetation becomes scorched and withered and rocks become burned and altered, leading to thermal radiation and spectral and structural anomalies on the surface. These features and spectral anomalies can be captured by remote sensing satellites and equipment. By analyzing these data, the range of a given fire area can be delineated and the extent of fire development in the area can be determined. However, all related information is obtained only from the surface and is therefore impossible to effectively detect hidden underground fire sources (Zhang et al., 2004a, 2003; Zhang et al., 2004b). (c) Surface thermometry. This method is rapid, covers a wide area, and is sensitive to changes in surface temperature and topography. However, the thermal profile of the coal fire zone more than 30 m deep is often not reflected on the surface (Kuenzer and Stracher, 2012; Litschke et al., 2008; Zhang and Kuenzer, 2007). (d) Magnetic detection. Magnetic minerals can develop in iron nodule-bearing rock formations, due to burning and associated high-temperature metamorphism, which can alter the magnetic properties of the rock mass and cause changes in the magnetic field near the fire area. The spatial distribution of an underground fire zone can therefore be discerned by observing changes in the magnetic field change at the surface. However, there are many additional magnetic remnants in the gob of a production mine, which can cause interference with regard to fire source detection (Schaumann et al., 2008; Shao et al., 2014; Tan et al., 2007). (e) Surface-based radon detection. Coal strata often include high concentrations of clay minerals, which contain radioactive elements (e.g., uranium, thorium, radium) that spontaneously decay to produce radon gas. This free-state radon can then migrate to the surface under the effects of convection, diffusion, and groundwater transport. Liu et al. (Liu et al., 1997) reported that high temperatures increase the emission coefficient of radon in a coal seam and nearby rocks, resulting in changes in the concentration of the overlying radon. Wang and Wu et al. (Wang, 2010; Wu et al., 2012) performed experiments simulating the spontaneous coal combustion process and reported a correlation between radon concentration and temperature in the processes of coal oxidation and heating. For example, radon concentrations were found to increase from 2.51 to 115.51 pCi/L with a coal temperature increase from 20 to 300 °C. Several field studies have applied the radon detection method to locate subsurface coal heating (Wu et al., 2006; Xue et al., 2008). Although the radon detection method is widely used in underground fire exploration, the description of detection steps and data processing have been simple and vague in literature, and verification often remains troublesome. Surface-based radon detection has the advantage of being a simple low-cost operation with high precision that is not limited by the detection terrain. Disadvantages include that the probe cup must be buried within a surface layer, and that water largely influences the radon concentration, as radon is highly soluble in water. In addition, this method is susceptible to the interference due to the development of fissures and fractures, which can serve as good channels for radon gas migration and lead to gas escape from the rock matrix. This may cause a sudden increase in radon concentration that may interfere with the location of the fire area (Hellmuth et al., 2017; Wilkening, 1980).

This study uses the gob of a small abandoned coal mine on the southwest side of the Bao Shan Yao Zhai coal mine (BSYZ) as a case study to investigate its spontaneous combustion areas. Because this small coal mine is located in a typical mountainous plateau covered by loess, the local climate is dry with little rain and no surface water, which provides favorable conditions for identifying fire areas using the surface-based radon detection method. Through the application of this method, the location, size, and development trend of fire sources in the gob of the small coal mine were determined.

2. Method of surface-based radon detection

2.1. Test instrument

An alpha cup emanometer (ACE) was used to measure radon concentrations, as shown in Fig. 1 (Ding et al., 2017). An ACE is composed of an ionization chamber, alpha cup (AC), charge sensitive preamplifier, and other circuits. When AC absorbing radioactive radon and its decay products is embedded in a cup-shaped mold on one side of the ionization chamber, radon tends to produce a large quantity of alpha particles. These particles can ionize the air and form ion pairs in the chamber. The produced ion pairs can then be converted into an electric pulse signal, which is amplified by a charge sensitive preamplifier and converted into a displayed pulse count (Ding et al., 2017). The pulse count per unit time is proportional to the radon concentration such that high-precision ACE measurements can accurately reflect the concentration of radon and its decay products at a given location. Radon in the soil can spread into the AC under the influence of a radon concentration gradient, air convection, and other factors (Ershaidat et al., 2008; Zhang and Hua, 1990). Four hours of burial time is sufficient to allow an adequate number of alpha-particle tracks to be detected in the low-radioactivity terrain. After about 4 h, the radon concentration in the AC will no longer change significantly, so it is considered that a dynamic radioactive equilibrium has been reached between the AC and soil (Ding et al., 2010; Xue et al., 2008). The AC can then be removed from the soil and placed in an ACE for a 3-minute measurement.

2.2. Steps for radon detection on the surface

To effectively detect fire sources due to the radon migration, the entire surface-based radon detection process can be divided into six steps, as shown in Fig. 2. First, measuring points and AC layout are selected according to the terrain layout. After the concentration of radon and its decay products reaches equilibrium on the AC inner surface, the AC is dug out and placed in the ACE for data measure-