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Categorical modeling on electrical anomaly of room-and-pillar coal mine fires and application for field electrical resistivity tomography

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ABSTRACT

In order to improve the accuracy of fire area delineation in coalfield with electrical prospecting, the categorical geoelectric models of coal fires are established according to geological and mining conditions. The room-and-pillar coal mine fires are divided into three types which are coal seam fire, goaf fire and subsidence area fire, respectively, and forward electrical simulations and inversion analysis of each type of coal fire are implemented. Simulation results show that the resistance anomalies of goaf fires exist around one and a half to two times higher than background field, in contrast, coal seam and subsidence area fires performance low resistivity response which are roughly half to two-third of background field resistivity, respectively. Identification of different fire types and delineation of coal fire areas are further presented. The inversion results which are validated by borehole survey prove that the presented method could eliminate the omission of coal fires with high resistance anomaly and provide a novel reference for fire extinguishing in the future.

1. Introduction

Coal fires, also known as underground coal fires, refer to the large-scale, long-term coal combustion phenomenon which gradually develops along the coal seam and not only causes large amounts of non-renewable coal resources burned out, but also cause pollution to the ecological environment (Kuenzer et al., 2007; Stracher & Taylor, 2004). Coal fires which are ignited by natural or man-made factors have normally occurred in major coal-producing countries such as China, the United States, Australia, India, Indonesia, etc., China is one of the countries that suffer the most serious coal fires (Song & Kuenzer, 2014). Coal fires in the arid western regions (such as Xinjiang, Inner Mongolia, Ningxia, etc.) of China are especially serious (Schaumann et al., 2008; Stracher, 2004). In order to provide a serviceable reference to fire extinguishing and guarantee the safety of the firefighting workers, locations of underground coal fires should be determined firstly and accurately.

Aiming to delineate the fire area, the development and evolution process of coal fires should be comprehensively understood. Previous researches have reported that the occurrence of coal fires is related not only to coal characteristics of itself such as metamorphic grade (Blasi, 1993), particle size (Liu & Zhao, 2006), pore structure (Lee et al., 2012), moisture content (Arisoy & Akgün, 1994), etc., but also to external influences such as ventilation and oxygen supplements (Nowak et al., 2008), a heat transfer conditions (Wang et al., 2016). Hence, the thermal dynamic evolution of coal fire is an extremely complicated and coupled process which is influenced by many factors such as coal oxidation (Wang et al., 2013), surrounding rocks (Weßling, 2007), leakage fracture, natural convection (Huang et al., 2001), etc. Due to these numerous factors and complex interactions, simulation method is economical and safe, so it was often adopted in studies on underground coal fire phenomena (Wang et al., 2011). Although many numerical models have been established to study the chemical and physical process of coal fires (Wessling et al., 2008), most of these models have just taken one or a few factors into consideration to study the evolvement patterns of coal fire (Huang et al., 2001; Song et al., 2014; Tang et al., 2015), and none of them has considered all processes involved from reaction kinetics at the beginning of coal oxidation to physical and chemical changes occurring to coal and surrounding rocks after burnout. Therefore, it is not easy to approach the real situation of underground coal fire merely through numerical simulation and further comparative analysis should be carried out combined with field measurements.

So far, variety kinds of in-situ measurements which are based on geophysical and geochemical methods have been developed and applied for coal fires detection (Chang & Wang, 2012; Chatterjee, 2006; Li et al., 2005). Among of them, temperature mapping is a direct and most accurate method, which through laying a large number of

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boreholes on the ground, to study the real heat evolution of underground fire directly. However, it is time-consuming and costly to carry out temperature mapping work in a large coal fire area (Kim, 2004). Besides, drilling operations in the fire areas may not only threaten the personal safety of workers but also lead to greater secondary disasters. Since it is difficult to investigate the real evolution process of coal fire through direct measurement, employing indirect detections on the ground can not only ensure the safety, but also can be realized economically in a huge area. At present, detection methods which have been applied for coal fires delineation mainly include remote sensing, infrared measurement of temperature, characteristic gas method, radon measurement method, electric method and magnetic method (Mahdipour & Dadkhah, 2012; Meyer et al., 2009). In general, each method has its advantages and disadvantages. For example, remote sensing method or ground infrared measurement is able to cover a large coalfield and obtain the surface anomaly (Mishra et al., 2011). Gases, radon and magnetic measurement method could delineate the border of coal fires effectively based on the ground survey data (Shao et al., 2014). However, due to the influences such as fracture development, buried depth, rock properties, etc., sometimes the anomaly information observed from surface has no vertical and direct relationship to the underground fire. In addition, the buried depth of fire center is hard to determine, especially when it is deeper than 30 m, there may show no significant anomaly on the surface (Greene et al., 1969). As so far, these methods mentioned above are usually employed in qualitative explanations of fire range in engineering practices (Shao et al., 2013).

Currently electrical methods have been successfully and efficiently used to conclude the burial depth and scope of anomalous bodies in cave exploration (Martínez-López et al., 2013), environmental protection (Neyamadpour et al., 2009), etc. The basic theories of electrical methods including direct current method, spontaneous potential method, and electrical resistivity methods are all based on the electrical characteristics of underground anomalous body (Karaoulis et al., 2014). For coal oxidation and self-ignition, related studies on variation in electrical property of coal and rock mass during combustion process have been carried out. Through experiments (Duba, 1977, 1983; Wan, 1982), it was found when the electrical resistivity of saturated coal sample increases with the temperature rising from 24 °C to 110 °C, and then it gradually decreases due to the rise of carbon content in the coal pyrolysis processing. After around 515 °C, the resistivity performances a sharply dropping and it is close to zero when the temperature passes 800 °C. For the surrounding rock, Xiong et al. (2006) tested the resistivity of rock samples (sandstone) collected from Wuda Coalfield. The results pointed a critical temperature of 500 °C that the resistivity changes complicatedly without any monotonic regularity to follow below this threshold, but it shows a rapidly decline when the temperature exceeds the critical value and it approximates zero at 900 °C. Furthermore, in-situ survey in mine fire areas also found significant resistivity anomalies, which could prove that electrical method can be used to detect coal fire (Bartel, 1982).

As for the preliminary applications of electrical method of coal fire detection (Li et al., 2005) theoretically analyzed the formation principles of spontaneous potential in fire areas and summarized the distribution patterns in the combustion process. By using this method, Shao et al. (2014) successfully delineated coal fire in Xinjiang Heshituoluogai Coal field and the measurement data also proved that the surface exists anomalous spontaneous potential above the fire area. In addition, adopting transient electromagnetic method, Schaumann et al. (2008) and King (1987) detected the

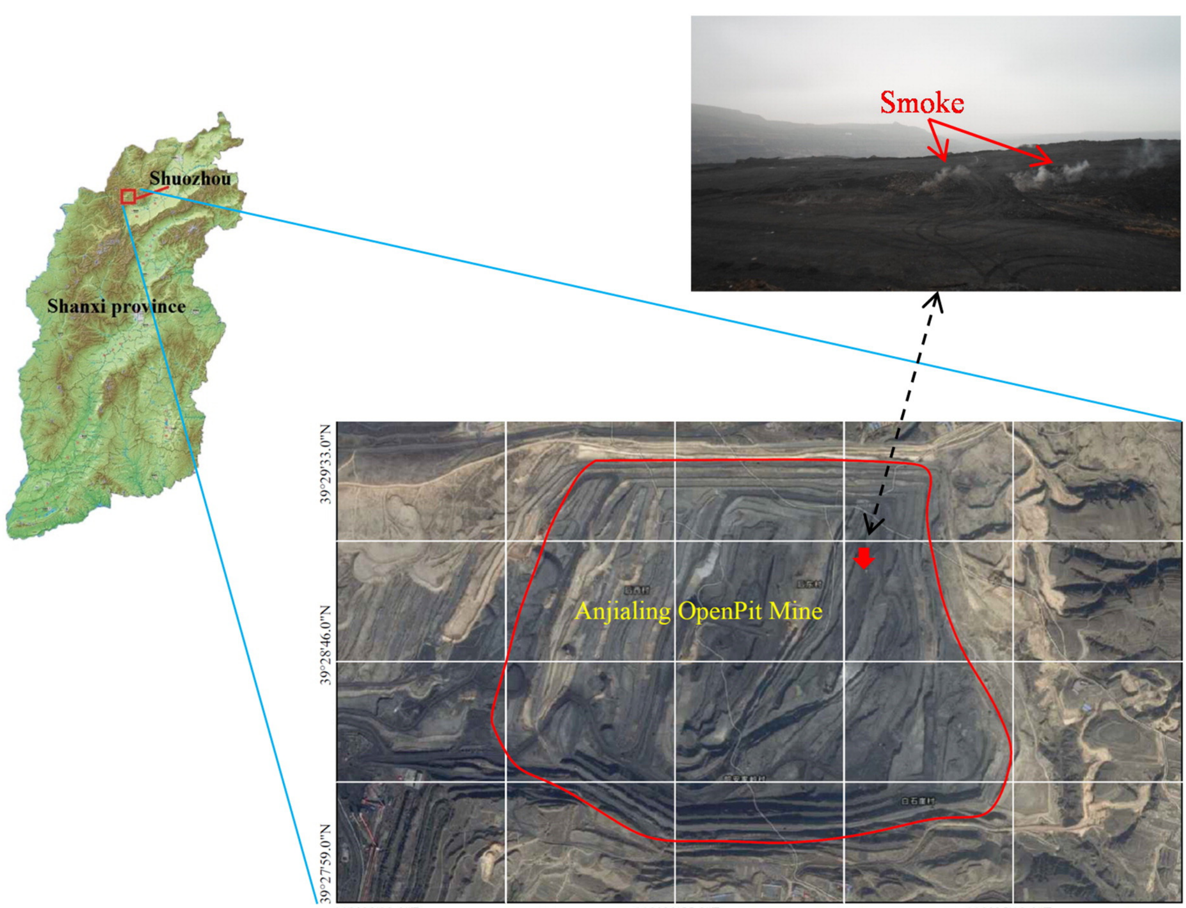

Fig. 1. The location of the mining area and the images of the fire area.