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Experimental study of the self-potential anomaly caused by coal fires

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ABSTRACT

Self-potential method has been used to detect coal fires for decades. However, the origin of self-potential anomaly relating to coal fires is still unclear. In this paper, we first analyze three possible sources of self-potential anomaly that relating to coal fires, i.e., the thermoelectric potential, the redox potential and the streaming potential, among which the streaming potential is negligible. Then, an experimental system is designed to research the above-mentioned three possible sources, in which six experiments are conducted finally. The results verify the existence of the thermoelectric potential and the redox potential. The self-potential that measured on the surface increases with the increase of temperature of the heat source, but decreases dramatically with the increase of its buried depth. Furthermore, the redox potential reduces the total self-potential values on the surface.

1. Introduction

Coal fires are fires that occur in underground coal seams featured with large area (several million square meters), high temperature (over 1000 °C) and long duration (decades or even hundreds of years). They are ignited by a process named spontaneous combustion, which occurs due to a natural reaction but is usually triggered through human interaction. Most currently burning coal fires are ignited through the influence of mining operations, which creates favorable conditions for spontaneous combustion (Zhang et al., 2004b; Zhang et al., 2007; Kuenzer et al., 2007; Shao et al., 2015). Many coal producing countries, such as China, India, the United States, and South Africa, suffer serious coal fires (Stracher, 2004; Stracher and Taylor, 2004; Zhang et al., 2004a; Künzer, 2005; Kuenzer et al., 2008; Kuenzer and Stracher, 2012; Song and Kuenzer, 2014; Song et al., 2015). The oldest known coal fire throughout the world is the Burning Mountain in Australia which has been burning for approximately 6000 years (Ellyett and Fleming, 1974). Coal fire at Kuhi Malik in Tajikistan has also been burning for thousands of years since the era of Herodotus.

Coal fires is now a global catastrophe that posing numerous economic and ecological impacts (Stracher and Taylor, 2004). They burn out non-renewable coal resource, which is a great loss for the state economy (Tan, 2000). The chaotic and uncontrollable combustion of coal fires release tremendous amount of toxic gases (such as CO and SO_2) and greenhouse gases (CO_2 and CH_4) into the atmosphere, which in turn intensify air pollution and global warming (Dai et al., 2002; Stracher and Taylor, 2004; Van Dijk et al., 2011; Kuenzer and Stracher, 2012). Moreover, huge amounts of heat and toxic substances (for instance sulfur, mirabilite and coal tar) generated by coal fires can destroy the physical and chemical properties of soil and lead to the death of vegetation (Rathore and Wright, 1993). They are also responsible for the release of contaminants (e.g. arsenic, fluorine and heavy metals such as mercury and lead) in aquifers. In addition, coal fires threaten the health of the local residents as well as the safety of their properties and facilities (Finkelman, 2004; Yang et al., 2005; Finkelman and Stracher, 2011). Take Jharia coal fire in India for example, large numbers of people were displaced from their home because of health problems associated with burning coal fires (Stracher and Taylor, 2004). In the United States, Centralia coal fire had reduced the town's population from 1100 residents in 1962 to 20 people in 2003 and to around 5 people in 2010 (Stracher et al., 2006, 2010).

Therefore, it is urgent to control existing coal fires, which will ensure the security of national energy, improve the ecological environment and protect the health of local residents. Before the implementation of the fire control/extinguishing work, the exact position of the fire must be delineated. This will ensure the fire control work being more targeted and efficient. Thus, the detection of coal fires is of paramount importance prior to developing any strategies to control or extinguish them. Many countries with existing coal fires, such as China, India, the United States, Australia, South Africa and Poland, have carried out significant work on the aspect of coal fire detection.

At present, primary coal fires detection methods include borehole temperature measurement, remote sensing, geochemical measurement and geophysical investigation (Wu et al., 2009; Shao et al., 2014). In general, borehole temperature measurement cannot be used for large-scale areas due to time-consuming and high cost. Remote sensing is only effective in detecting near surface fires (deeper than 30 m)

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(Greene et al., 1969). The low resolution of the remote sensing image (only 20–100 m) is another drawback. Geochemical measurement can be easily affected by the characteristics of the strata overlying the combustion area and by the climatic conditions (Li and Zhang, 2006). The most commonly geophysical methods used in the detection of coal fires are magnetic method and self-potential method, which have delineated plenty of coal fires for several decades (Zhang, 2004; Shao et al., 2014). The origin and signature of magnetic anomaly derived from coal fires have been widely researched since 1963 (Hooper, 1987; Bandelow and Gielisch, 2004; Sternberg and Lippincott, 2004; Zhang, 2004; Gielisch, 2007; Sternberg et al., 2008; Shao et al., 2014). However, articles about the origin/mechanisms of self-potential anomaly caused by coal fires are rarely published (Revil et al., 2013).

In this paper, we first discuss three possible sources of self-potential anomaly relating to coal fires, i.e., the thermoelectric potential, the redox potential and the streaming potential. However, the streaming potential is negligible in coal fire area due to the absence of water pressure head. Then, an experimental system is designed to study the thermoelectric potential and the redox potential. Finally, six experiments are conducted respectively to study the signature of thermoelectric potential, the influence of temperature and buried depth of heat source on it, as well as the emergence and magnitude of the redox potential.

2. Possible self-potential sources relating to coal fires

The self-potential method was proposed by Robert Fox in 1830 who used a copperplate electrode with a galvanometer measuring device to detect the copper-sulphide deposits in Cornwall, England (Reynolds, 2011). The electrical field associated with the existence of in situ sources of electrical currents is measured between two points on the surface of the earth (Revil et al., 2012). Since 1920, this method has been used in the exploration of metal deposits, ground water and geothermal field. Self-potential method is a passive and non-invasive geophysical method because it does not cause any disturbance to the earth (Nyquist and Corry, 2002).

Various source currents of self-potential signals exist in nature, which can be related to the flow of pore water (streaming current, c.f. Abaza and Clyde, 1969; Revil et al., 1999; Revil et al., 2003; Rizzo et al., 2004), the diffusion of ionic species (diffusion current, see Ikard et al., 2012), the gradient of redox potential in the presence of chemical reaction or an electronic conductor (redox current, e.g. Naudet et al., 2004; Risgaard-Petersen et al., 2012), and the less-known thermoelectric effect (thermoelectric current, see Revil et al., 2013; Ikard and Revil, 2014; Shao et al., 2014). The above currents are source terms in the Maxwell equations to generate an electrical field, which in turn forms the corresponding potentials (Revil et al., 2012), i.e. the streaming potential, the diffusion potential, the redox potential, and the thermoelectric potential.

The self-potential signal that relating to coal fires may mainly contain three components: thermoelectric potential caused by temperature gradients, redox potential generated by violent oxidation (i.e., combustion) of coal, and streaming potential deriving from the migration of water.

2.1. Thermoelectric potential

The combustion of underground coal releases huge amount of heat. The temperature around the burning center is generally several hundred or even exceeds one thousand degree Celsius. However, due to the high heat capacity and low thermal conductivity of sedimentary rocks, it is difficult for heat to transfer to the ground surface. Therefore, temperature on the ground surface is much lower than that in the burning center. Charge carriers (electrons and holes) in the rocks have higher thermal velocities on the hot side and thus diffuse more quickly from the hot side to the cold side than in the opposite direction. This indicates there will be a net flux of charge carriers from the hot side to the cold side. The flowing charge carriers build up on the cold side (i.e., ground surface), and this separation of charges creates a potential difference between the two sides which counters this charge imbalance. Consequently, the thermoelectric potential could be measured on the ground surface. This current density is a source term in the Maxwell equations, which generates electrical and magnetic field disturbances (Revil et al., 2013).

2.2. Redox potential

The essence of coal combustion is a rapid and violent chemical reaction between combustible components and oxidant, usually atmospheric oxygen, releasing heat, light, and various reaction products. Coal (mainly consists of carbon) reacts with oxygen producing CO_2, CO and other products. According to the experiments conducted by Schmidt et al. (2003) and Lohrer et al. (2004), a simplified reaction formula of coal and the heat released were obtained:

$$C_{48}H_{65}S_1O_{26} + 26\ O_2 \rightarrow C_{26}H_{17}O_{10} + 24\ H_2O + 2\ CO + 20\ CO_2 + SO_2 + 2.19 \times 10^7\ \ J\ kg^{-1} \quad (1)$$

During the exothermic chemical process, coal loses electrons, which will flow through the rocks to the surface where they will be recombined by a terminal electron acceptor (Risgaard-Petersen et al., 2014). In this process, coal serves as the electron donor at the anode and oxygen gas serves as the terminal electron acceptor at the cathode. The flow of electrons provides the source current density, which serves as source term in the Maxwell equation to form one of the components of self-potential, i.e., redox potential.

2.3. Streaming potential

Minerals that initially contained in rocks will dissolve in water, which will form mineralized solution. The double layer (solid-liquid) is formed between the rock particles and mineralized solutions. In general, rocks (porous media) have an excess of positive charge in their pore water to balance the fixed charge occurring on their particle surface. The streaming current associated with the drag of the excess of charge by the flow of water corresponds to an advective flow of electrical charges and therefore a net source current density. This could be another source term in the Maxwell equation, which forms another component of self-potential, i.e. the streaming potential.

$$\Delta V_S = \frac{\epsilon_f \xi}{\eta_f \sigma_f} \Delta P \quad (2)$$

where, ΔV_S refers to the streaming potential, ϵ_f is the fluid relative permittivity, ζ denotes the zeta potential, η_f denotes the fluid viscosity, σ_f denotes the fluid conductivity, ΔP is the fluid pressure difference. It's clear from this equation that the streaming potential is proportional to the water pressure. However, coal fires usually occur in arid areas where water is scarce and groundwater pressure is almost equal to zero. Although water can be generated from the combustion of coal and water vapor could migrate to the ground surface through fissures and cracks, the water pressure gradient along these channels is not sufficient to form streaming potential and thus is negligible.

Thermoelectric potential, redox potential, and streaming potential are the three possible sources (or components) of self-potential anomaly relating to coal fires. According to the above-mentioned analysis, the streaming potential is negligible and won't be included in the present study. Consequently, the main sources are the thermoelectric potential and redox potential. In the following sections, several experiments that modeling the self-potential anomaly in coal fire area are conducted to study these two sources. In addition, how some factors (such as the temperature and the depth of the fire) influence the magnitude of self-potential anomaly will also be studied.