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# Time-varying characteristics of electromagnetic radiation during the coal-heating process

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ABSTRACT

Forecasting and predicting coalfield fire and coal concealed fire are difficult components of coal fire control, and there is currently a lack of widely applicable effective methods for these processes. Electromagnetic radiation (EMR) has the advantage of multi-direction cross-locating and has been widely used to monitor and provide early warnings for coal and rock dynamic disasters. In this paper, the time-varying characteristics of EMR during 3 metamorphic grades of the coal-heating process were studied. EMR signals were clearly generated in different metamorphic grades of the coal-heating process. The variation trend of the EMR signals was different for 3 metamorphic grades of coal. According to *R/S* statistical analysis of the EMR signal time series, all Hurst values were greater than 0.5 and the correlation coefficient was above 0.9. There is a positive correlation between the EMR signals and coal temperature. In the coal-heating process, the EMR signal intensity varied if the EMR test frequency was 1 kHz, 15 kHz and 50 kHz. Thermal deformation and thermal cracking of the coal body occurred in the coal-heating process. The free electrons and electric dipole in coal migrate and generate EMR. Based on the changing characteristics of the EMR in the coal-heating process, we present the conceptual design of a method to detect concealed fire in underground mines.



## 1. Introduction

Ecological, safe and green mining of modern mines has become the development theme of coal mining worldwide [1,2]. In the coal mining process, the temperature of coal, which can spontaneously combust, automatically increases under certain oxygen supply conditions, and a fire will ultimately occurs because of spontaneous combustion of coal. Coal fires pose great threats to valuable energy resources, the environment, human health and safety and seriously threaten mine safety [3]. Coal fire is one of the most serious disasters in coal mines. The toxic and harmful gas produced by coal combustion polluted the working environment and significantly damages the ecological environment [4].

Coal fires have occurred in numerous countries: the most affected countries are China, India, the USA, and South Africa [5,6]. Fifty-six percent of the coal seams in China have a spontaneous combustion tendency; the amount of burning coal exceeds 20 million tons because of coal fire every year. In the western coal areas of China, the coal spontaneous combustion period is a short, simple geological condition, with a shallow bury and large air leakage. The XinJiang, Inner Mongolia, NingXia, and ShanXi provinces have a serious risk of coal fire [3].

Coal is a chemically reactive organic material which can combine with oxygen and generate heat [7]. Coal fires basically result from the spontaneous combustion of coal in goaf. The volatile and water content in coal represents the reactive component. It is considered to be one of the most statistically significant factors in determining the self-heating propensity of coal [8]. The effect of lignite with different water contents on the spontaneous ignition of coal has been studied [9]. The spontaneous ignition temperature of coal char first decrease with the decreasing volatile content and subsequently rapidly increase when the volatile content continues to decline [10]. Coal fire has the characteristics of causing serious damage and a wide range. It is difficult to find the fire source in an underground coal field, such as a broken coal pillar or spontaneous combustion of the coal in the goaf. Finding the fire location is also difficult even if there is a spontaneous symptom or coal spontaneous combustion [11]. Coal fires are difficult to extinguish, and can easily relapse. The detection and location of hidden fire sources in a mine are difficult tasks that are needed to prevent and control coal fires. It is necessary to effi-

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ciently and quickly predict the occurrence of a fire and locate the fire danger source.

After several decades of exploration and development, coal fire detection and monitoring can be categorized into four groups: underground, ground, airborne, and space borne investigations [3]. Among them, the temperature detection method is widely applied in coal concealed fire detection [12]. The temperature detection method has the advantages of accurate positioning. A direct thermometer is drilled from the ground or underground to the goaf, where spontaneous combustion may occur. Then, a install thermal detector is installed in the borehole to determine the position of fire source. In the gas detection method, $CO_2$, CO, $CH_4$, $H_2$, $C_2H_4$, $C_2H_2$, and higher hydrocarbon gases are produced during coal spontaneous combustion [13]. The gas type and concentration are not identical during the coal oxidation heating process, so they can be used as judgment data of the temperature and degree of coal spontaneous combustion. According to gas concentration gradient approximation, we can determine the scope of the spontaneous combustion hazard and spontaneous combustion fire area [14]. Index gases are a cost-efficient and effective approach to detect coal fires. It is not necessary to drill boreholes to obtain underground combustion information. However, in practice, index gases are generated from other sources; for example, the work face produces $CH_4$ from underground during coal mining, which can mislead coal combustion prediction [3]. Temperature variation causes changes in magnetic values [15]. Because the magnetic anomaly distribution range caused by spontaneous combustion is closely related to the coal fire burning area, by measuring and analyzing the magnetic field of the underground coal seam spontaneous combustion area, we can determine the change of burnt rock and effectively distinguish different phases of coal combustion, which guides fire extinction.

There have been many developments to detect coal mine fires using the above methods. However, large statistical errors are often generated because of the limitations of the geological conditions and limited precision of the detecting instruments. The accurate detection of coal temperature changes in hidden fire danger areas, which can allow the mine staff understand and master the fire development process, has an important guiding role for fire prevention.

## 2. Basic guidance of coal fires detection

The coal mass produces a thermal effect because of the physical and chemical action of coal and oxygen and forms a thermal storage environment. The coal oxidation process can be divided into the slow-oxidation phase at low temperatures and the fast-oxidation stage at high temperatures [16]. The thermal properties of the bituminous coals indicated that the thermal behaviors are responsible for its self-heating from 50 °C and spontaneous ignition at 80 °C; at approximately 150 °C, a new set of coal-oxygen complexes exothermically form [17].

When the temperature reaches the ignition temperature, burning occurs in the coal mass. The burning center develops along the deep part of the coal seam if oxygen is continuously supplied. A fissure in the coal-rock mass in coalfield fires is simultaneously formed by the high temperature, and a burnt empty area is developed [18]. Under the action of heat and pressure, the fissure field provides transport channels to supply fresh oxygen from the surface to the fire area, which keeps the coal mass burning [19]. This is the development and evolvement process of coalfield fires, which reveals the rule that the burning center of coal mass further develops along its deep part in coalfield fires [20,21]. The current geophysical methods are remote sensing infrared thermal imaging, magnetic and self-potential methods [3]. Coal heat can produce potential changes; the self-potential anomalies in coal fire areas derive from two aspects: the redox potential generated by the oxidation of coal and the Thomson potential caused by temperature gradients [15]. In addition, the high temperature due to burning may decrease the resistivity of coal or rock. The low-resistivity area detection can contribute to judging the combustion boundary or combustion center. Although an empty area is formed by a collapsed roof at the combusted area, the empty area has higher resistivity than the surrounding rock, which is the premise of using the electrical property to detect holes using the electromagnetic method [22].

The above analysis shows that magnetic and electromagnetic signals can be produced in the combustion process of a coal fire. The EMR signal is produced by the deformation and fracture of coal [23]. Macroscopic deformation and fracture characteristics appear during coal and rock mass heating. The μCT225kVFCB type high precision micro CT test system was used to study the relationships between thermal cracking and temperature changes in brown coal and gas coal [24]. When lignite was approximately 100 °C, the large fracture was dominant. At approximately 200 °C, the medium fracture was dominant. After 300 °C, micro-cracks were dominant. The pore fissure developed before 300 °C mainly because of thermal cracking. The deformation characteristics of anthracite coal under thermal-mechanical coupling conditions [25], that occur with the increase of temperature are as follows: 20–200 °C is the thermal expansion stage, 200–400 °C is the slow compression stage, and 400–600 °C is the sharp compression stage.

The macroscopic deformation and fracture characteristics of the coal body under temperature treatment have been described. Coal rock deformation and fracture can produce EMR signals. Therefore, in the thermal damage process of coal, EMR signals are related to the thermal deformation and thermal cracking. The change laws of the EMR variation characteristics from coal heating can reveal the temperature effect on EMR signals and propose a new method to detect concealed fire in coal mines using the EMR technology.

Scholars have extensively studied the EMR characteristics of coal rock deformation and fracture under loading conditions. EMR signals are generated by induction of a transient electric dipole, separation of the crack edge charge with crack propagation and relaxation of the separation charge of the crack wall [26]. The stress state and coal gas effect on the EMR signals change characteristics, and the coal and gas outburst can be predicted using the EMR method. EMR signals were produced by the external force of coal using the EMR method to determine the coal combustion, gas drainage and stress redistribution near the coal working face [27]. Based on the relationship between the energy of the EMR signals from two orthogonal antennas and the receiving angle, the direction of the coal deformation and fracture was determined [28]. The generation mechanism, characteristics and propagation characteristics of the EMR from coal and rock deformation and fracture [29,30] were used to provide early warnings of coal and gas outbursts, predict rock bursts, and monitor and predict the coal mine goaf roof stability [31,32].

The EMR energy and EMR count are the basic measurement parameters of EMR signals. These parameters can better reflect the deformation and fracture of coal rock. EMR technology is one of the most promising non-contact detection methods, and EMR has the advantages of orientation and multi-direction cross-locating. In this paper, we established the EMR testing experimental system during coal heating and burning. The characteristics of the EMR time series of different metamorphic degrees of coal during the heating process were studied. The variation characteristics of EMR at different test distances were analyzed and combined with the characteristics of EMR at different frequencies to reveal the generation mechanism of EMR signals during coal heating and burning. Borrowing from the characteristics of EMR during