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ORIGINAL ARTICLE

Study on the electromagnetic spectrum characteristics of underground coal fire hazardous and the detection criteria of high temperature anomaly area

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Abstract
Electromagnetic radiation (EMR) is an optimal non-contact and directional geophysical detection method, which has been applied in geotechnical engineering, monitoring and giving early warning about the coal and rock dynamic disaster. In this paper, the different frequencies EMR signals generated in the process of coal heating and spontaneous combustion are tested and analyzed, and the detection criterion of locating anomalous heating areas by EMR is illustrated. During the spontaneously-heating process of coal, the EMR signals are detected by antennas with frequencies of 30 kHz, 100 kHz, 300 kHz and 1 MHz, covering both low and high frequencies. In the process of coal spontaneous combustion, the spectrum of EMR signal changes with the increase of coal temperature. The amplitude of EMR also fluctuates, showing the characteristics of high frequency and high amplitude, and the corresponding thermal damage of coal occurs in different degrees (intensities). Further, in order to use EMR as an effective detection method of coal fire, the relationship between the intensity of EMR and coal size, test distance and temperature is discussed. With the dominant spectrum of EMR determined by field tests, researchers can employ different EMR frequency to detect the fire risk based on the concrete conditions of coal field. This study provides a meaningful method for improving the level of safety and environmental protection during mining process.

Keywords Coal spontaneous combustion · EMR · Dominant spectrum · Fire location · Fire zone boundary

Introduction

The study of the characteristics of coal spontaneous combustion is fundamental for spontaneous combustion risk analysis, fireproof material research, mining safety process design and fire prevention practices (Pan et al. 2018; Guo et al. 2019; Hao et al. 2019). There is a huge demand for efficient and fast non-contact detection of underground coal fires and location of fire sources. Detection and early warning of coal spontaneous combustion is a difficult point for fire prevention and control work, which is of great significance to the protection of the environment. However, it is difficult to detect hidden spontaneous combustion in the early stage of formation such as spontaneous combustion of coal field, goaf, broken coal pillar and coal storage pile (gangue hill) (Song and Kuenzer 2014; Qi et al. 2018; Cui et al. 2019). It is necessary to detect the occurrence of coal spontaneous combustion and locate the fire source efficiently and quickly (Kong et al. 2019a, b; Li et al. 2019a, b, c, d). Furthermore, if the danger of spontaneous combustion in coalfield can be forewarned, the development and expansion of coal spontaneous combustion can be prevented before the expansion of spontaneous combustion of coal (Kong et al. 2017a, b; Tang and Wang 2019).

When coal or rock is damaged, it releases energy, including mechanical energy, sound energy, and electromagnetic energy. The infrared radiation method is an effective

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detection method in detecting coal spontaneous combustion based on the above energy release (Deng et al. 2019). Coal-rock EMR is a phenomenon that coal-rock and other materials dissipate energy in the form of electromagnetic waves in the process of deformation and fracture (Wang et al. 2011). Both infrared and visible light belong to the category of EMR, but their frequencies and wavelengths are different.

In the process of prevention and control of coal and rock dynamic disasters, coal-rock EMR technology is a new geophysical exploration technology. The former Soviet Union and China studied it earlier while the United States, Germany and Japan also carried out research on EMR (Yoshida and Ogawa 2004; Reinhard and Greiling 2010). Rock EMR is developed from the research on earthquake early warning, and has made great progress in earthquake prediction (Nitsan 1977).

EMR technology is a relatively successful detection method, and is widely used in disaster detection in coal mine safety mining (Frid 1997; Lichtenberger 2006; Airuni et al. 1985). At present, based on the theory of coal-rock EMR, the method of real-time monitoring and early warning on coal-rock dynamic disasters by EMR is invented, and the early warning criteria of coal-rock dynamic disasters are established (Wang et al. 2011).

According to the current research, both coal and rock would produce EMR signals during the heating process based on the laboratory test results (Kong et al. 2018a, b, c). The mechanism of EMR produced by coal and rock heating is as follows: in the process of coal heating, free electrons and dipole groups are generated and electromagnetic waves are emitted. The EMR generated by coal heating is the result of thermal expansion deformation and thermal expansion cracking (Liu et al. 2020; Zhang et al. 2020; Zhang et al. 2021). Through further study, it is found that the free radical chain reaction of coal can also produce EMR during coal temperature rising and combustion (Kong et al. 2019a, b).

The EMR signals of coal and rock have a good correlation with temperature. The potential EMR signal of coal sample in small volume size in the process of heating rupture is tested, the characteristics of electric signal in the process of heating coal sample are analyzed, and the changing characteristics of potential signal in the heating process of coal pile are further studied (Kong et al. 2018b, c; Wang et al. 2019; Yu et al. 2020).

At present, the detection method of EMR in coal spontaneous combustion has not been involved. In the field test of EMR in coal spontaneous combustion, the selection of test distance and the reception of EMR information are related to the selection of test spectrum. Problems like what is the change rule of EMR signal in coal field fire? When applying EMR to field detection, how to use EMR to locate the areas with abnormally high-temperature, all need to be solved. The study provides a meaningful method for promoting the mining safety.

In this paper, the different frequencies EMR signals generated in coal's heating process and spontaneous combustion are tested and analyzed, the detection criterion of locating anomalous heating area by EMR is illustrated, and the coal field in Urumqi, Xinjiang is selected as the research target in the EMR detection of the coal field fire.

Experimental

In terms of the previous EMR research on the heating process of coal-rock and other materials, since aluminum materials can generate EMR information (Srilakshmi and Misra 2005), therefore, when selecting experimental equipment, the interference of materials on EMR signals should be avoided.

Based on above analysis, an experimental system of EMR for coal heating is constructed. The system can study the variation of EMR, temperature and index gases during coal heating at different scales. The EMR experimental system for coal heating is shown in Fig. 1.

The experimental system consists of heating chamber (material of heating chamber can be referred to the literature by Kong et al. (2018b), heating device, temperature

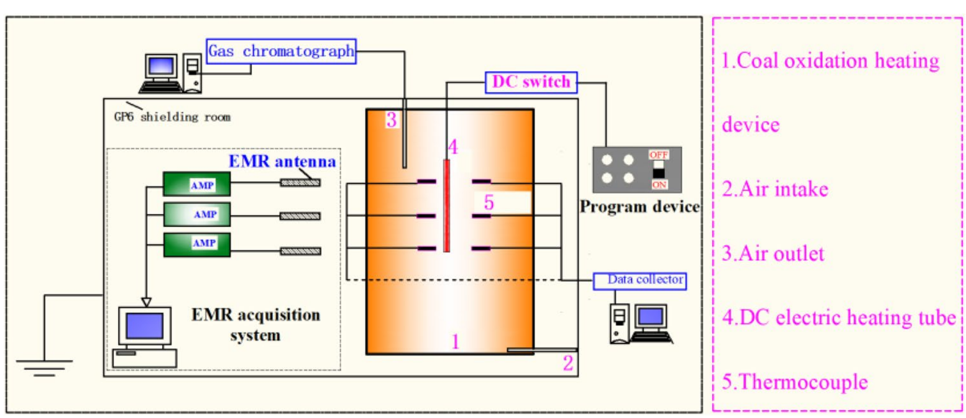


Fig. 1 Experimental system diagram (Kong et al. 2018b)

measuring system, EMR testing system and gas testing system. The heating system and temperature measuring system diagram can be seen in Fig. 2.

The heating system consists of a temperature control device, a rectifier switch and a DC heating tube. Since the alternating current can produce alternating EMR interference signal, the rectifier switch is used to convert alternating current into direct current. The maximum power of the rectifier switch is 960 W and the output voltage is 48 V. The heating tube is a special DC dry heating tube with a rated power of 500 W.

The coal samples needed for the experiment are taken from Shuozhou Bai Lu (BL) coal mine in Shanxi. The samples are fresh and intact, and the bulk of coal samples is wrapped with fresh-keeping film and transported to the testing and analysis center. According to the industrial analysis, the industrial indicators for moisture (%), ash (%), volatile (%), density (g/cm^3) are 3.72, 26.42, 38.14, and 1.72, respectively, and the spontaneous combustion tendency is II.

During the experiment, in order to simulate the real environment of coal spontaneous combustion as much as possible and test different EMR signals accurately, the experiment is carried out based on the following simulations and settings:

1. The heating method of direct current is used to test and analyze the heating of coal, so as to avoid the interference of alternating current to test EMR signal.
2. In order to realize the testing and analysis of EMR signals at different frequencies, we independently design and process EMR test antennas combining with directional spot frequency and broadband frequency. The antenna frequencies are 30 kHz, 100 kHz, 300 kHz and 1000 kHz.
3. During the test, the DC electric heating tube is used to heat the abnormally high temperature area of the simulated coal field fire area. The maximum temperature of the electric heating tube is 400 °C. The coal body contacts with the electric heating tube, and the temperature gradually increases.
4. Before the start of the experiment, first it is necessary to carry out the debugging of EMR equipment, and the most important thing is to adjust the threshold value of signal acquisition. And the study conducts three empty tests without coal separately to complete the shielding of all the interfering electromagnetic signals before proceeding to the experimental test.

When conducting on-site testing of anomalous high-temperature areas of coalfield fires, the EMR test equipment used in this article is a test equipment independently developed by China University of Mining and Technology. The EMR testing entity device is shown in Fig. 3.

Results and discussion

EMR scale effect during coal heating and combustion

The changes of EMR signals in two cylinder shape size are tested, and the results of cylinder shape size and EMR measurement are shown in Fig. 4.

As shown in Fig. 4, the EMR signal of size 1 is obtained from BL coal by heating test. The cylinder shape size 1 is diameter 320 mm and height 400 mm ($d \times h$: 320 × 400 mm) and the coal is in a loose state. The EMR signal of cylinder shape size 2 is obtained by heating test of standard raw coal sample, and the cylinder shape size 2 is diameter 50 mm and height 100 mm ($d \times h$: 50 × 100 mm). Under the two cylinder shape size, the EMR signal increases with the increase of temperature, but the variation law of the EMR signal is different. It shows that the EMR measured value of the larger one is higher than that of the smaller one and the EMR signal of the larger one is more abundant than the small cylinder shape size in the whole heating process.

Fig. 2 The heating system and temperature measuring system diagram

Fig. 3 EMR testing device

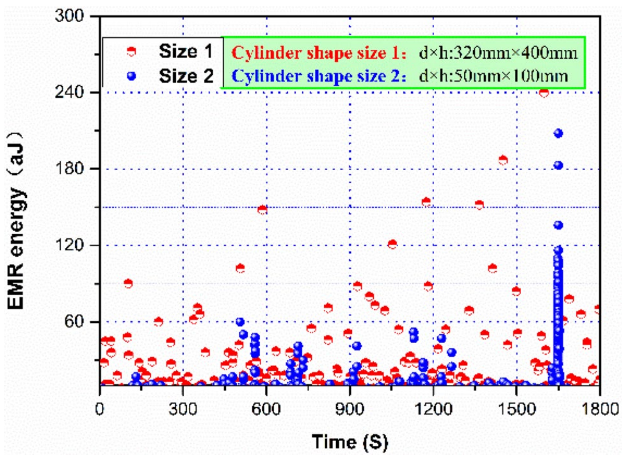


Fig. 4 The changes of the EMR value of BL coal under different cylinder shape size

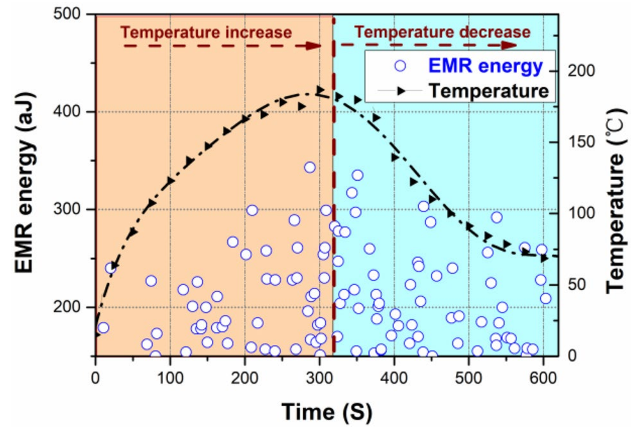


Fig. 5 The change of EMR signals in the process of heating and cooling of BL coal

The reason for the above results is that the contact area is different. The coal in large cylinder shape size is in a loosely stacked state, correspondingly its body's heating rate is faster than the smaller one. And the intensity and frequency of EMR produced by coal during heating are different. When the coal in large cylinder shape size is heated, the accumulated heat inside its body is larger and the temperature rises quickly, so the measured maximum value of EMR signal during the whole heating process is higher than that of the small cylinder shape size.

Changes of EMR signals during coal temperature increasing and cooling process

The changes of EMR signals of coal in the temperature increasing and cooling processes are tested. The results of EMR test are shown in Fig. 5.

As shown in Fig. 5, it can be concluded that the EMR signal has a good correspondence with temperature in the heating process of coal, and EMR signal changes with the change of temperature. When coal is heated, the temperature rises rapidly, so does the EMR signal. The temperature of coal continues to rise, and the EMR signal continues to increase. The measured value of EMR increases from 0 to 350 aJ at this time, and the temperature of the coal surface has reached 175 °C. After the heating stage, when the heat source is closed, the temperature of coal body decreases. The EMR signal will increase temporarily due to the thermal action of coal body, and then the intensity of EMR will decrease and change.

After analyzing the change law of EMR signal in the heating and cooling process of coal, it can be obtained that the changing trend of EMR signal has a certain corresponding relationship with the change of temperature, especially in the temperature rising stage. This shows that the EMR signal generated by heating the coal body is a process of energy accumulation and release in the coal body. The higher the temperature is, the more significant the thermal deformation and cracking of the coal body become, and the greater the value of the EMR signal is. When the temperature is reduced to 175 °C, energy still accumulates inside the coal body, making the EMR still change after the temperature is reduced to a certain fluctuation.

The changing trend of EMR with temperature shows that the test and inversion of the area where coal is heated and withstand high temperature can be tested and inverted through the law of EMR sequence. The higher the coal temperature is, the greater the energy accumulated inside the coal is, so the tendency of the EMR signal to increase becomes greater.

EMR change characteristics of different frequencies

The EMR signals of BL coal during spontaneously-heating process are tested experimentally. The measured waveform signals contain all the EMR information. The variation of EMR at different frequencies is shown in Fig. 6. It should be noted that Fig. 6 shows the overall changing trend of EMR pulse and time. The increase of time corresponds to the increase of coal temperature. As a bridge through time, it is possible to analyze the trend of EMR pulse with temperature.

Figure 6 shows the changes of EMR measurements with receiving frequencies of 30 kHz, 100 kHz, 300 kHz and 1 MHz. The EMR measurements vary with different frequencies. As a whole, the EMR measurements show an obviously increasing trend with the increase of heating time. However, the changing trends of the number of EMR pulses at different frequencies are different, and the magnitude of the measured values at the same time is also different. During the spontaneously-heating process of BL coal, the variation of EMR values at different frequencies with the increasing time is shown in Fig. 7.

It can be seen From Fig. 7 that the measured values of EMR at different frequencies are obviously different during the heating process of BL coal. At the same time, the measured values of EMR from large to small are 300 kHz, 1 MHz, 100 kHz and 30 kHz. The changing trend of EMR at different frequencies is significant for analyzing the dominant frequency range of EMR. By testing different frequencies, the best receiving frequency can be selected to carry out the field test of EMR in covert fire of coal spontaneous combustion.

Changes in the spectrum of EMR during spontaneously-heating process of coal

The main frequency characteristics of EMR of four groups of BL coal during heating process are analyzed. The main frequency variation of EMR is shown in Fig. 8.

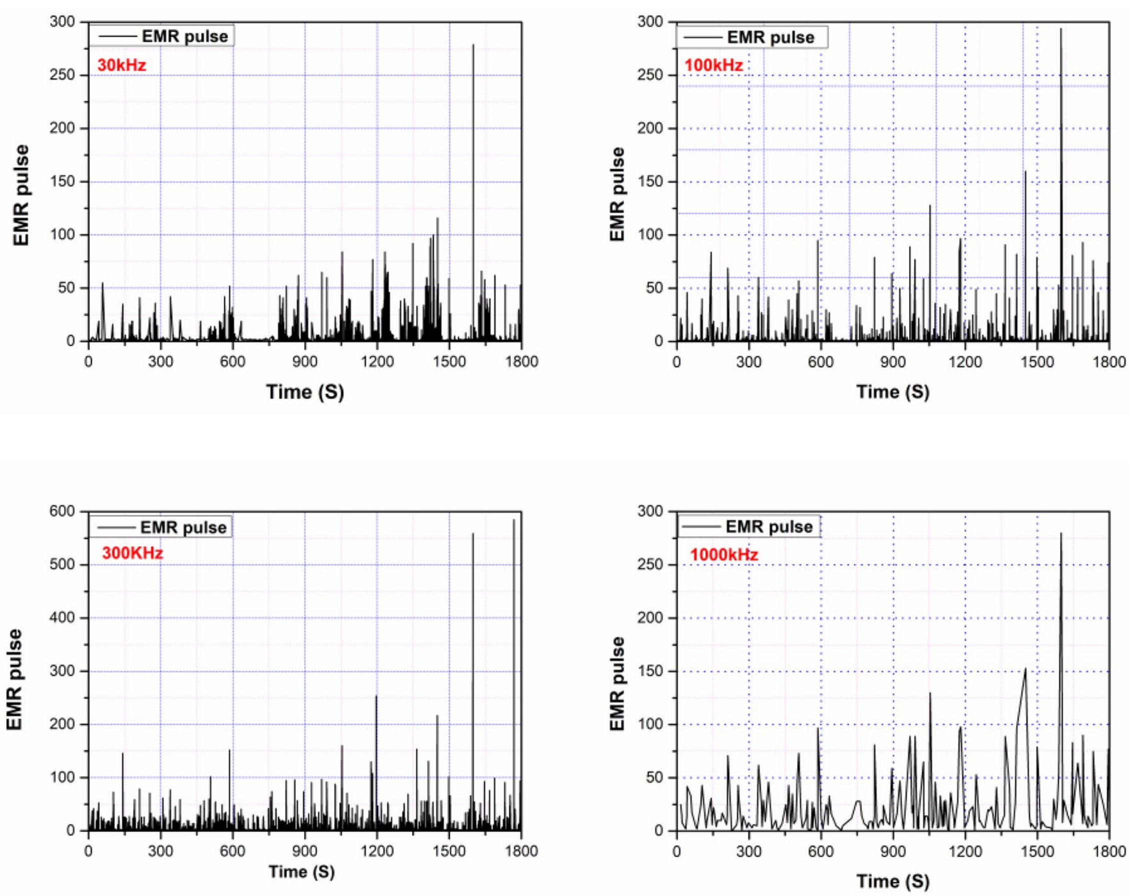


Fig. 6 Variation of EMR pulse at different frequencies (BL coal)

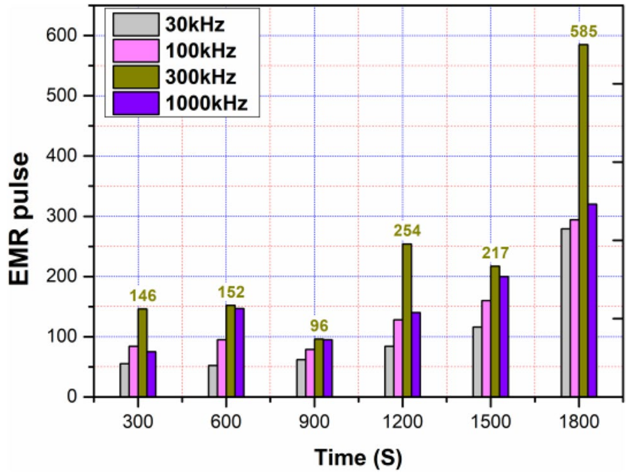


Fig. 7 Variation of measurement value of EMR at different frequencies

As shown in Fig. 8, the main frequency of EMR signal in Text 1 changes gradually when coal is heated. When coal is initially heated, the main frequency of EMR varies around 100 kHz, while the secondary frequency varies around 600–700 kHz. When temperature is 112 °C, the main frequency of EMR varies significantly around 100 kHz, and the frequency band of EMR signal varies significantly around 900 kHz. The main frequency of EMR signal in Text 2 varies most significantly from 350 to 500 kHz. The main frequency band of Text 3 has the most significant change. At the beginning of heating, the main frequency of EMR is the largest about 700 kHz, and the main frequency of EMR covers the widest frequency range. When the temperature rises to 79 °C, the EMR has an obviously high amplitude in the range of 700 kHz and 900–1000 kHz. In Text 4, the main frequency band of EMR is also wider, and the main frequency changes obviously.

Statistical analysis shows that the main frequency of EMR varies in the heating process of three kinds of coal as shown in Table 1.

Through the comparative analysis, it can be concluded that the main frequency of EMR is higher in the spontaneously-heating process of coal, and the range of EMR frequency band can reach between 1 kHz and 1.5 MHz, with the widest frequency band. When analyzing the characteristics of the main frequency, it is found that with the increase of temperature, the main frequency of EMR also changes obviously in the low frequency region.

During the heating process of coal, the main frequency of EMR has the characteristics of increasing range, fluctuating change and low frequency amplitude. The main frequency variation of EMR indicates that the EMR signal can characterize the evolutionary process of coal's internal state during heating. The higher the temperature is, the more obvious the

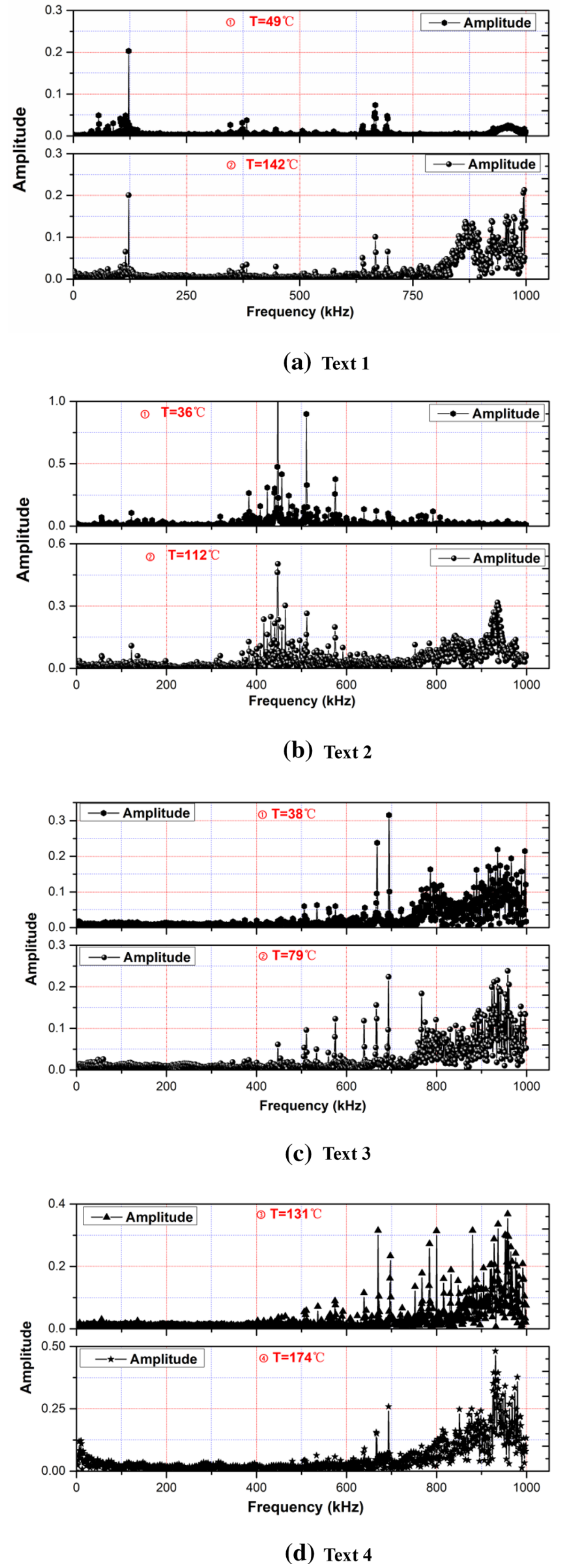


Fig. 8 EMR spectrum characteristics of BL coal. **a** Text 1. **b** Text 2. **c** Text 3. **d** Text 4

Table 1 Main frequency band distribution of EMR

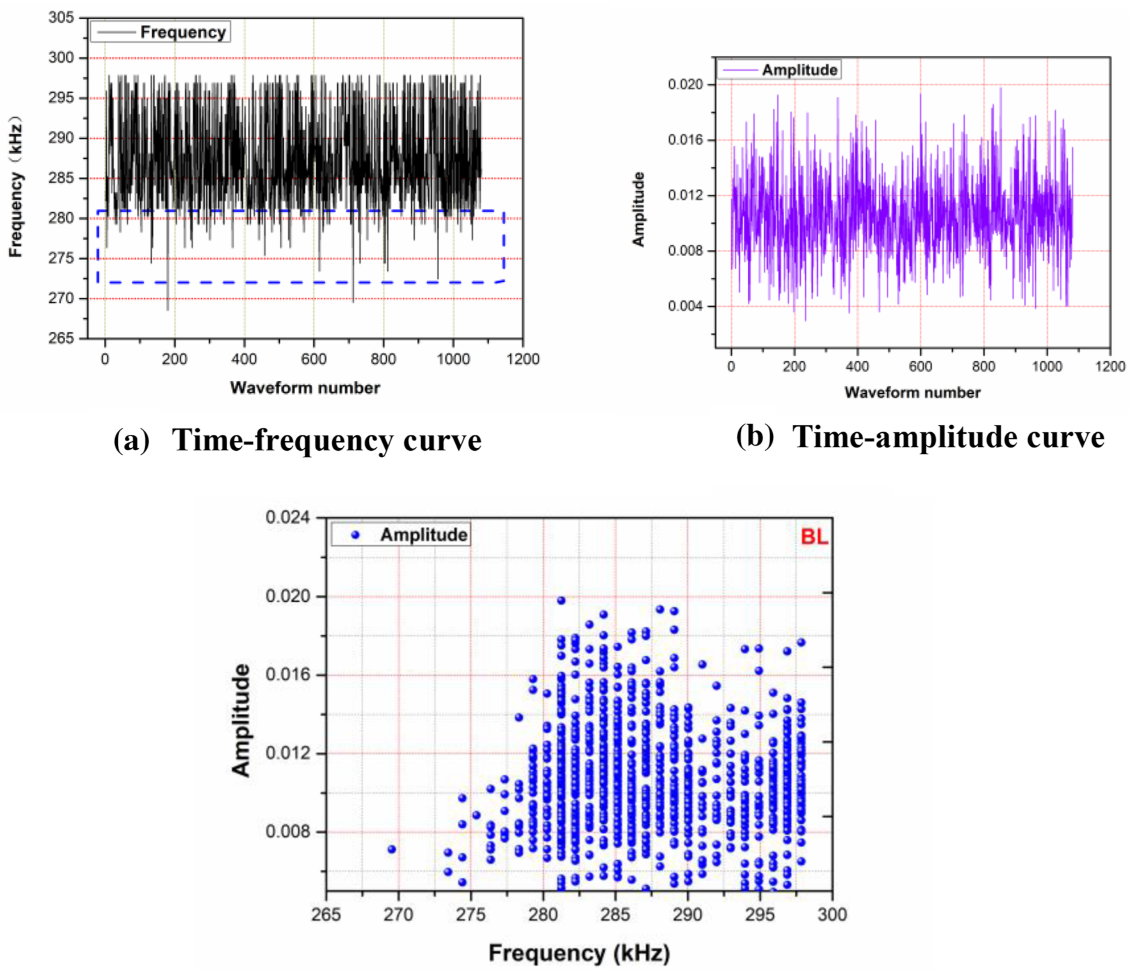
Coal	BL			
Main frequency	100–150 k	350–550 k	650–700 k	600–1000 k
Sub main frequency	800 k–1 M	800 k–1 M	800 k–1 M	700 k and 800 k–1 M
Change characteristics	Range increase, fluctuation change, low frequency amplitude change			

main frequency and secondary primary frequency response of EMR become. By analyzing the spectrum characteristics of EMR and choosing the appropriate spectrum of EMR, researchers can receive coal heating EMR information more comprehensively.

Spectrum analysis of EMR signals in coal combustion process

The spectrum changes of EMR signals during the whole process of coal combustion can be used to characterize more detailed information about EMR signals of coal combustion. Taking BL coal as an example, the spectrum analysis of EMR signals of coal during heating combustion is carried out. The main frequency and amplitude changes of EMR signals are shown in Fig. 9.

Figure 9 shows that the main frequency of EMR fluctuates from 260 to 300 kHz during BL coal combustion. The variation of the main frequency and amplitude indicates that the intensity and frequency of electromagnetic signals generated during coal heating and combustion are constantly changing. The amplitude of EMR also fluctuates,



(a) Time-frequency curve (b) Time-amplitude curve

(c) Frequency-amplitude curve

Fig. 9 Changes of main frequency and amplitude of EMR during coal heating and combustion (BL coal). **a** Time–frequency curve. **b** Time–amplitude curve. **c** Frequency–amplitude curve showing the changing characteristics of high frequency and high amplitude. The magnitude of amplitude indicates the intensity of deformation and fracture of coal and rock, which indicates that the coal body is damaged with different degrees (intensity) during the process of temperature rising. The variation of EMR amplitude can reflect the process of deformation and fracture of coal combustion at elevated temperature. The characteristics of EMR frequency are influenced by the internal structure of coal body, temperature and other factors. At the same time, the flame produced by coal combustion also has some influence on EMR.

Field measurement and location of high temperature abnormal areas by EMR

Generation mechanism of EMR in coalfield fire zone

The generation of EMR from deformation and fracture of coal and rock is directly related to the accumulation of free charge and the change of electron acceleration. EMR is closely related to the process of loading, deformation and fracture of coal and rock mass. The electromechanical effects (including piezoelectric effect, Stepanov effect, friction electrification, damage and fracture of double cushion) and electrodynamic effects of coal and rock mass are the sources of EMR (Wang et al. 2011).

There are two parts in the electromagnetic field produced by the charge migration and the variable speed motion of the free charge during the deformation and fracture of coal-rock mass: one is the Coulomb static electric field produced by the charge movement, i.e. the induction field; the other is the radiation field produced by the change of the acceleration of the free electron. The size of the radiation field is related to the acceleration of electrons, and the radiation field is also related to the distance between charges and the density of electrons (Kong et al. 2018a, b).

(2) EMR mechanism of coal combustion flame

In the process of coal spontaneous combustion, the main form of activation energy to stimulate ionization is thermal energy, but activation energy also includes mechanical energy, thermal energy, light energy and so on. Therefore, the generation of electrons needs to satisfy the activation energy and that the change of energy (reaction enthalpy) in the reaction process is larger than the ionization energy of materials. The generation of charged ions in the flame of coal combustion is shown in Fig. 10.

As can be seen from Fig. 10, due to the action of activation energy, the combustion substances in the flame are decomposed by heat and chemically ionized to produce ions (cations and anions) and free electrons with different ionic properties. The internal anions of the flame accumulate with a large number of negative charges, and the

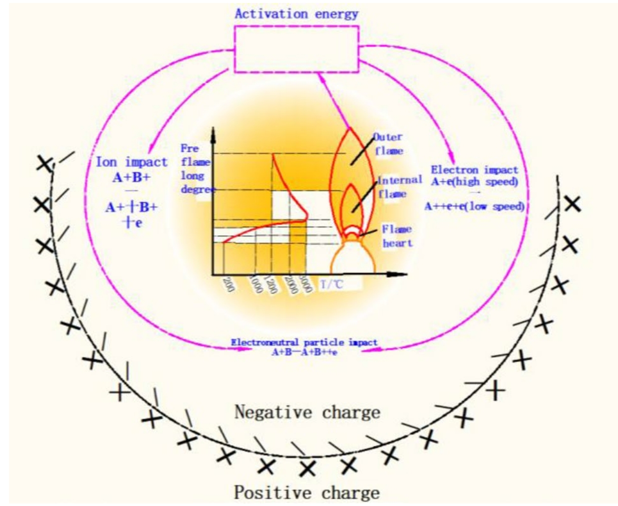


Fig. 10 A schematic diagram of charged ions produced by flame

cations accumulate at the position of the external flame with positive charges. The accumulation of charged ions with different electrical properties causes the formation of induced electromagnetic fields around the flame, which generates EMR.

The higher the temperature is, the higher the concentration of free electrons is. The accumulation of free electrons causes the electrostatic field around them to radiate electromagnetic signals. Furthermore, with the chain reaction process of charged ions in coal flame, the continuous generation and disappearance of charged ions make the coal flame radiate a large number of free electrons outward, and EMR can also be generated in the process of the generation and disappearance of free electrons.

Dominant frequency selection

According to the theory of electromagnetic wave propagation, the propagation velocity of electromagnetic wave in medium is as follows (Wang 2009):

$$v = \frac{\omega}{a} = c/n_x. \quad (1)$$

Among, v is the velocity vector of the charged particle, ω is the wave frequency, c is the speed of light, n_x is the refractive index, and a is the reciprocal of the wavelength.

If the amplitude of electromagnetic wave decreases by e times in the medium of coal and rock mass, the distance of EMR propagation is regarded as the effective distance of electromagnetic wave propagation L. L is defined as the effective penetration depth of electromagnetic wave (Wang 2009):

$$L=\frac{1}{b}=1/\sqrt{\frac{\mu_m\omega^2}{2}\left[\sqrt{\varepsilon_r^2+\left(\frac{\rho_e}{\omega}\right)^2}-\varepsilon_r\right]}=1/\sqrt{\frac{\mu_m\varepsilon_r\omega^2}{2}\left[\sqrt{1+\left(\frac{\rho_e}{\omega\varepsilon_r}\right)^2}-1\right]}. \tag{2}$$

In the formula, ε_r is the dielectric constant, μ_m is magnetic permeability, H/m, ρ_e is the conductivity, F/m.

In the analysis of the effective distance L, the formula (2) is simplified according to the theory of reference (Kong et al. 2018a), namely:

$$b=\sqrt{\frac{\omega\mu_m\rho_e}{2}} \qquad L=1/\sqrt{\frac{\omega\mu_m\rho_e}{2}}. \tag{3}$$

According to the above analysis and the electromagnetic characteristic parameters (ε_r, ρ_e) of coal and rock mass, the relationship between the frequency f and propagation distance L of EMR is calculated:

$$L=\sqrt{\frac{\rho_e}{\pi\mu_m f}} \qquad f=\frac{\rho_e}{\pi\mu_m L^2}. \tag{4}$$

The resistivity of coal ρ_e generally ranges from 10^2 to 10^3. Without considering the influence of temperature on coal's resistivity, the longest distance that can be detected in the field is 22.5 m when the maximum receiving frequency of EMR f is selected 500 kHz according to Eq. (4). When the upper limit of receiving frequency is 20 kHz, the detection range (or depth) of EMR is 35.6–112.5 m. The increase of test distance meets the needs of field test of the coalfield fire to a great extent, and is conducive to the layout and selection of test points. Therefore, the advantage of deep testing of low frequency signal should be taken into account in the selection of dominant spectrum of EMR in coal fires.

Analyzing the best receiving frequency of EMR can provide the best frequency for on-site testing, thereby increasing the testing distance, so as to ensure the detection of sufficient range of EMR information, and carry out EMR anomalous analysis and fire inversion.This is also the most concerned issue for EMR detection of the anomalous high-temperature areas in coal fields. At present, the detection and positioning can be achieved by the arrival time of electromagnetic waves and acoustic waves. Through the current analysis method of electromagnetic wave arrival, the arrival information of the two sensors at the optimal frequency can be settled, and EMR can be used to locate the areas with anomalously high temperature in coalfield.

An algorithm for locating high temperature anomalous regions by directional location of EMR

When testing EMR in anomalously high temperature areas, assuming that the coil turns of the electromagnetic antenna are N, the coil area is S, and the angle between the direction of the antenna and the abnormally high temperature area is θ. According to the theory of electromagnetic field, the magnitude of induced electromotive force E_m during field testing is obtained (Wang 2009; Kong et al. 2018b):

$$E_m=N\frac{d\phi}{dt}=N_s\cos\theta\frac{dB}{dt}. \tag{5}$$

If the power of the EMR received by the antenna is P, then P is proportional to the quadratic of the induced electromotive force E_m of the antenna and inversely proportional to the impedance R of the antenna. Namely:

$$P=\frac{E_m^2}{R}. \tag{6}$$

Based on this, the relationship between the energy and power W of EMR in any period of time is as follows:

$$W=\int_{t_1}^{t_2}P dt. \tag{7}$$

Combining with the above analysis, it can be concluded that the energy of EMR and the antenna test direction are proportional to the square of the angle between the radiation sources. $W \propto \cos^2\theta$.

It is assumed that the energy of the EMR source in the high temperature region is W, and its horizontal EMR energy is W_1, corresponding to the direction angle of W and W_1 is θ_1. The EMR energy of W in the vertical direction is W_2 and the direction angle between W and W_2 is θ_2. According to Eqs. (5)–(7), the following results can be obtained:

$$\frac{W_1}{W_2}=\frac{W\cos^2\theta_1}{W\cos^2\theta_2}. \tag{8}$$

The above formula shows that the direction of EMR source can be calculated by the energy value of EMR in horizontal and vertical directions, i.e. the main direction of EMR, in which the angles between the main direction of EMR and the horizontal and vertical directions are respectively: $\theta_1=\arctan\sqrt{W_2/W_1}$ and $\theta_2=\arctan\sqrt{W_1/W_2}$.

The total energy produced by heating and warming of coal-rock mass can be expressed as follows: $W=\sigma\varepsilon=\sigma^2/E$. The energy of EMR W_E produced by heating coal and rock mass is proportional to that of W, that is to say, the energy of EMR is as follows:

$$W_E = aW = a\sigma\varepsilon = a_e\sigma^2, \tag{9}$$

where a and a_e are proportional coefficients, σ is the thermal stress, ε is the thermal stress deformation.

According to electromagnetic theory, the relationship between EMR energy W_E and EMR intensity E_m is as follows:

$$W_E = \int_V w_e dV = \int_V \frac{1}{2} E_m D_e dV = \frac{1}{2}\varepsilon_r E_m^2 V. \tag{10}$$

w_e is the energy unit of EMR. V is the volume of coal and rock heated. D_e represents the potential shift of coal and rock heated. ε_r represents the dielectric constant of coal and rock materials.

When coal-rock mass are heated and heated, the volume and dielectric constant of it changes relatively so small, so Eq. (10) can be expressed as follows:

$$W_E = bE_m^2. \tag{11}$$

According to formulas (9) and (11), the intensity of EMR can be obtained. $E_m = k\sigma$, k is constant. That is to say, the EMR intensity of coal and rock heating is proportional to the thermal stress.

The dangerous degree of coalfield fire area is divided into areas with non-spontaneous combustion, or spontaneous combustion, and the corresponding EMR intensity is E_{wz}, E_z and E_{yz}, respectively. The critical value coefficients of the three corresponding risk degrees are:

$$k_z = \frac{E_z}{E_{wz}}, \quad k_{yz} = \frac{E_{yz}}{E_{wz}}. \tag{12}$$

Formula (12) is the criterion for judging the dangerous degree of coal fires.

Dominant frequency selection of EMR in field text

Xinjiang's coalfield fires are serious, but a large number of fire areas have not been identified. The fire area of Daquan Lake is relatively close to the city of Urumqi, about 9 km away. The Daquan Lake fire area in Xinjiang is dry, with shallow coal seams, short spontaneous fires and other typical coal field fire conditions.

When conducting field tests, the author first uses GPS high-precision tester to measure latitude and longitude, and the specific measurement value is east longitude 87°25′29.71″–87°27′17.25″, north latitude 43°47′31.23″–43°47′57.15″. The zoning characteristics can be clearly seen in the section of the coalfield in Fig. 11.

The fire area affects the surrounding ecological environment and people's living and life. The buried depth of the abnormally high temperature area in the Daquan Lake fire area in Xinjiang is about 10–100 m from the shallow surface, and the location of it can be detected by electromagnetic radiation technology.

In order to avoid the influence of the nearby areas with abnormally high temperature on the EMR test, when selecting the site, two-part setting is made: the first selected area is small and will not be affected by adjacent areas; the second is that we use directional antennas for directional detection.

After high temperature treatment, the interior particles change into igneous rocks, and the color changes. The on-site testing instrument selects self-developed electromagnetic radiation tester. The frequency of EMR testing antenna ranges from 0 to 100 kHz, and three groups of antennas for testing are selected, namely low-frequency directional magnetic rod antenna (10 kHz, 30 kHz), directional magnetic rod antenna (60 kHz) and EMR broadband antenna spectrum (ranging from 0 to 500 kHz). Variation trend of EMR signals at different frequencies is shown in Fig. 12.

According to the selected test site, the EMR test device is used to test the anomalously high temperature areas of coalfield. The results show that the EMR signal can be tested by using three different antennas. When the test frequency is 10 kHz, 30 kHz and 60 kHz, there are obvious EMR signals.

By comparison, it is found that the EMR signal with a frequency of 10 kHz is richer, and the amplitude is higher than 15 kHz, and when the electromagnetic radiation is at a frequency of 30 kHz, the amplitude is lower than 10 kHz. The EMR signal with a frequency of 60 kHz is not as large as the EMR signal with a frequency of 10 kHz.

The reason for the differences in EMR signals at different frequencies is that the EMR frequency is related to the

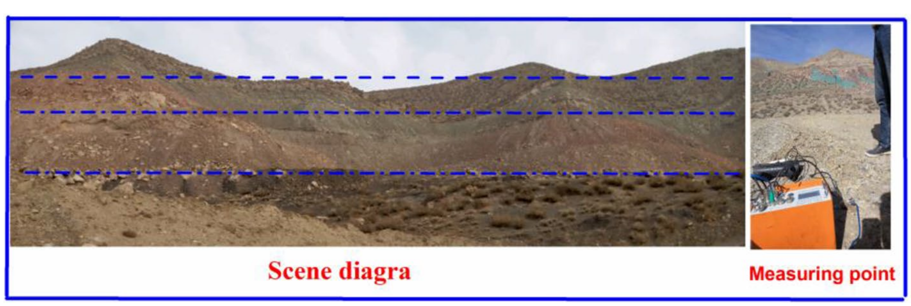


Fig. 11 Slope map of coal field

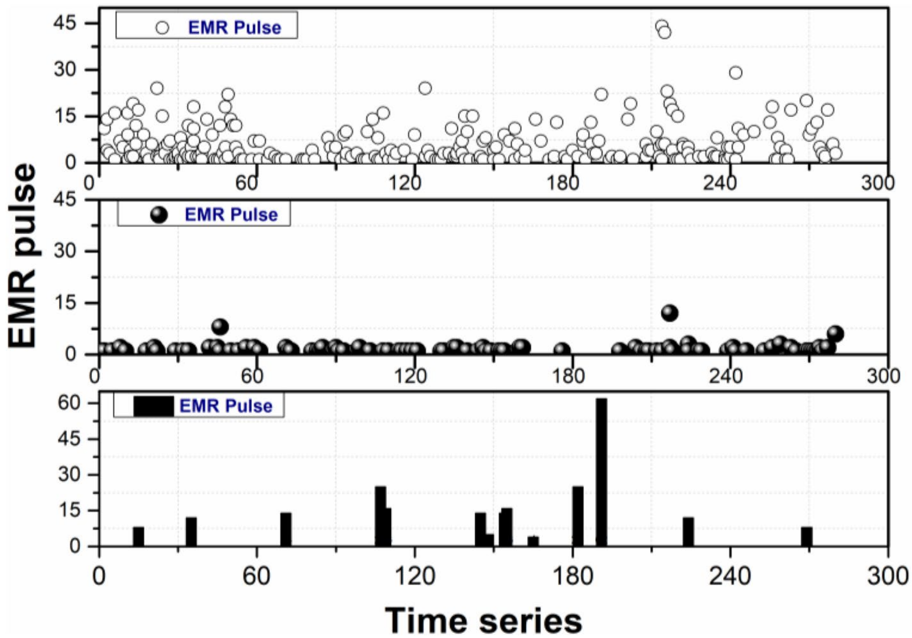


Fig. 12 Variation trend of EMR signals at different frequencies

test distance and the conductivity of the tested coal. When a coalfield fire occurs, the anomalously high temperature area of the coalfield is gradually evolving, and the temperature has a fluctuating process. At the same time, due to the different test time, the temperature of coal spontaneous combustion is also different. This causes differences in EMR signals at different frequencies.

The variation of the EMR signal is different, and the magnitude of the EMR signal pulse of different frequencies varies greatly. EMR pulse can be used to test the areas of abnormally high temperature in coalfield.

Conclusions

1. During the process of coal spontaneous combustion and heating, the EMR signals are detected by antennas with frequencies of 30 kHz, 100 kHz, 300 kHz and 1 MHz, covering both low and high frequencies. The changing trend of four kinds of frequency of the EMR signals is basically the same, and they all increase with the increase of temperature. The measured values of EMR signals vary with different frequencies. The measured values of EMR at different frequencies are 300 kHz, 1 MHz, 100 kHz and 30 kHz, respectively at the same measuring time.
2. The spectrum of EMR signal changes with the increase of coal temperature during the spontaneously heating-process of coal. The range of EMR frequency band can reach 1 kHz–1.5 MHz. With the increase of temperature, the amplitude of EMR changes obviously in the low frequency band. The main frequency of EMR shows the characteristics of widening the band, fluctuating and changing the low frequency and high amplitude. The higher the temperature is, the more obvious the response range of the main frequency of EMR is, which further shows that the change of the main frequency of EMR can characterize the damage state of coal when coal is heated.
3. The changes of EMR signals in different sizes of coal heating and combustion are analyzed. The measured values and intensities of EMR produced by the large size during heating are higher than those of small size. Besides, the mechanism of EMR during coal heating and combustion is revealed. The flame of coal combustion produces charged ions, and electromagnetic signal occurs in the chain reaction process of the generation and disappearance of charged ions.
4. The algorithm of locating anomalously high temperature areas by EMR is analyzed theoretically, and the criterion to determine the dangerous degree of the area's coal fire is given. The EMR test device is used to test the anomalously high temperature areas of coalfield. The results show that the EMR signal can be tested by using three different antennas. When the test frequency is 10 kHz, 30 kHz and 60 kHz, there are obvious EMR signals. The study provides a meaningful method for promoting the mining safety.

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