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Review

Early Detection of Coal Spontaneous Combustion by Complex Acoustic Waves in a Concealed Fire Source

Jun Guo, Haoyu Shang,* Guobin Cai,* Yongfei Jin, Kaixuan Wang, and Shuai Li

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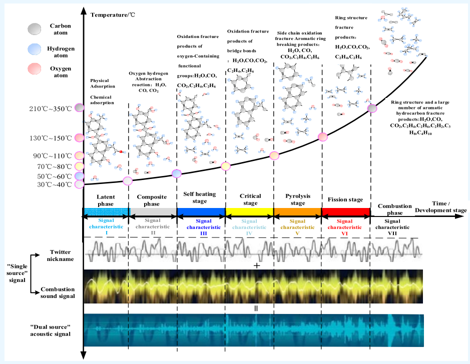
ABSTRACT: Prevention and control of coal spontaneous combustion are key to coal mining and storage. Existing technologies for the detection of coal spontaneous combustion have limitations, but coal spontaneous combustion creates some serious disasters in areas of the world where coal mining and/or storage exists. New technologies to detect coal spontaneous combustion are urgently needed to reduce the loss of life and resources. The article reviews the main techniques employed to detect coal spontaneous combustion and their advantages and disadvantages; it also reviews the good application prospect of acoustic temperature measurement technology on coal spontaneous combustion and introduces the basic principle of acoustic coal temperature measurement. The evolution of combustion sound and the propagation and attenuation of acoustic waves in quasi-porous media are discussed to form the basis for the development of acoustic thermometry technologies that can be used to accurately identify acoustic signals and temperature fields in loose coal. The concept of "single-source" coal temperature measurement to "dual-source" coal temperature measurement achieved by using combustion sound and an additional sound source device in the automatic combustion of loose coal in the mined area is discussed. The deep learning methods and correlation analyses are available to map the relationships between combustion sound, coal temperature, and sound velocity, and acquire coal temperature from dual source composite acoustic signals. The study lays the foundation for the development of acoustic thermometry technologies that have applications in different stages of combustion and applied to the early warning, prevention, and control of spontaneous combustion in coal, and it contributes to improving the environmental safety and efficiency of coal mining and storage.



1. INTRODUCTION

Coal is a primary energy source. Many research studies focus on the safe mining and storage of coal around the world. Coal spontaneous combustion creates some serious disasters associated with coal mining and storage. It is the process in which the coal body with the tendency of spontaneous combustion, when it meets the oxygen in the air, carries out oxidation to produce more heat than the heat dissipated to the surrounding environment, and heat gathering occurs so that the coal temperature rises to the ignition point and catches fire (Figure 1).[1−5] In the latent period of coal combustion, the main influencing parameters are water content, oxygen concentration, and the degree of coal deterioration, etc.[6] The location of the fire is often hidden, so the present technology is difficult to identify and control the fire. In the later stages, the high heat generation rate results in the heating of large portions of the coal, and the likelihood of controlling the fire decreases exponentially. Spontaneously combusting coal in restricted spaces such as mines and coal bunkers oxidizes at low oxygen levels and reignites readily; high temperature areas are highly mobile and difficult to detect. The detection, prevention, and control of areas of high temperature in spontaneously combusting coal are common problems in areas of the world where coal mining and/or storage exists (Figure 2).[7−15] Therefore, accurate and early detection of spontaneous combustion is the key to efficient control of associated fires.[16−19]

At present, areas of coal spontaneous combustion high temperature are mainly detected using fiber optic pyrometers, isotope radon measurement, resistivity probes, geological radars, and electromagnetic and other techniques. Qiang et al.[20] and Huang et al.[21] studied coal-related fires on a global scale and concluded that fiber optic pyrometry can be used effectively to monitor the temperature and determine the extent of the some coals spontaneous combustion. For isotope radon measurement, Ribeiro et al.,[22] Cheng et al.,[23] and Xu et al.[24] studied the complex coalfield fire zone in close coal seams and reported that the exact location of spontaneous combustion in coalfields can be precisely determined. Shao et al.,[25] Hui et al.,[26] and Wang et

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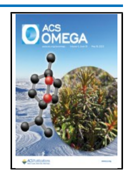

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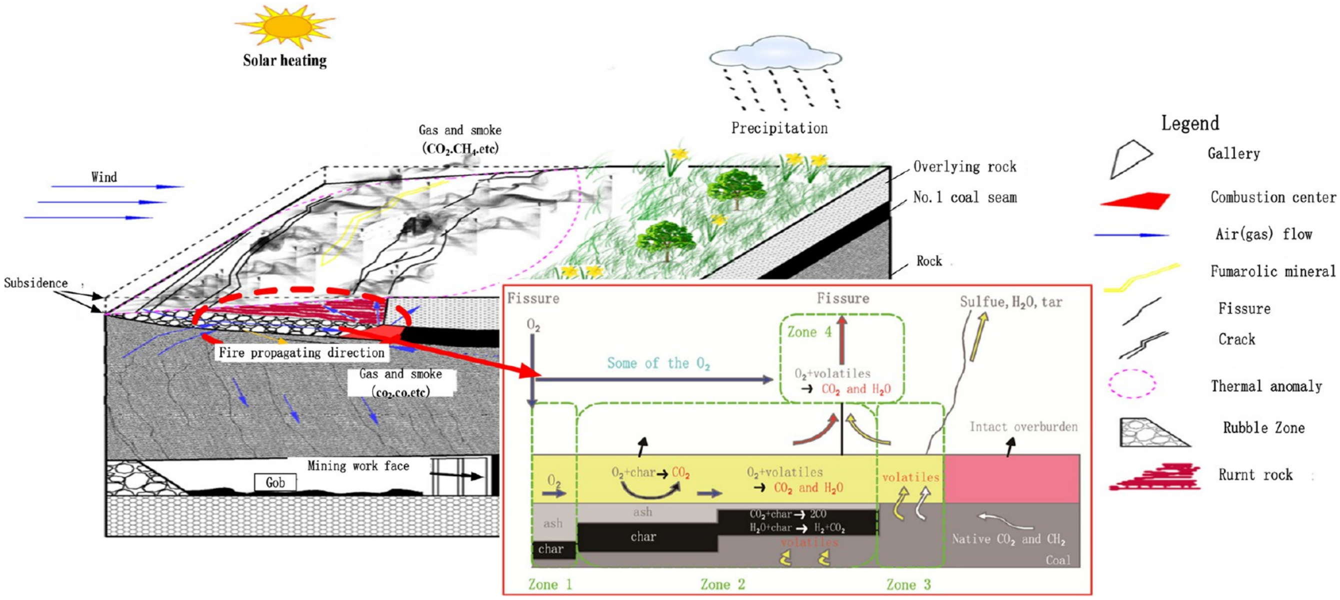

Figure 1. Development of coal spontaneous combustion.[2,3] Adapted with permission from ref 2, Copyright 2014, International Journal of Coal Geology; Adapted with permission from ref 3, Copyright 2011, International Journal of Coal Geology.

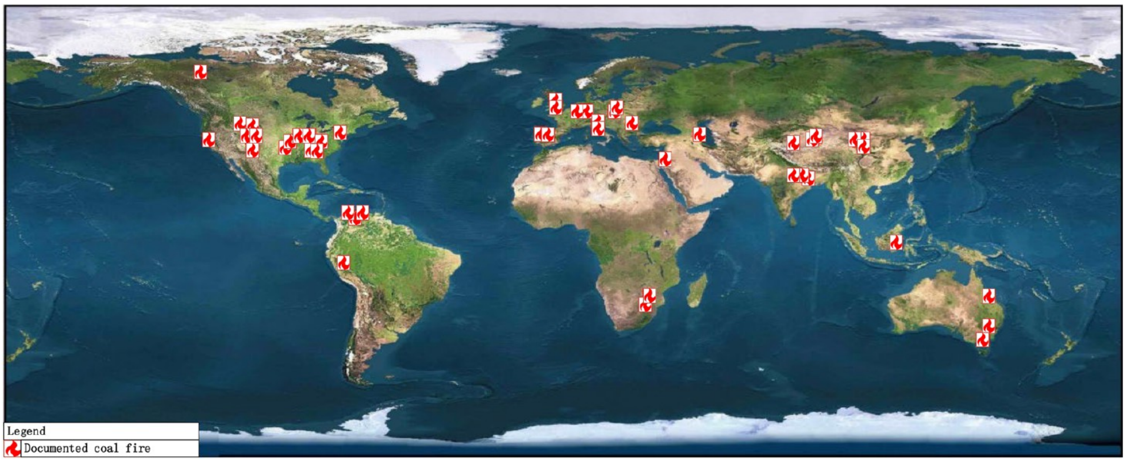

Figure 2. Global distribution of major coal fires.[9] Adapted with permission from ref 9, Copyright 2015, International Journal of Coal Geology.

al.[27] investigated coal samples under load and the mechanism of spontaneous combustion; they concluded that a change in resistivity accurately reflects the temperature change during spontaneous combustion. Du et al.[28] and Ma et al.[29] studied the high temperature areas in spontaneously combusting coal and reported that geo-radars can be used effectively to determine the central location of underground fires and combustion diffusion. Kong et al.[30,31] studied the changes in the electromagnetic spectrum with temperature during coal spontaneous combustion; they concluded that the high frequency and high amplitude electromagnetic signals can indicate the level of combustion and can be used to improve the accuracy of combustion detection.

Existing techniques for detecting high temperature points of spontaneous coal combustion have, for the most part, solved the problem of defining the extent of the fire zone; however, it remains difficult to obtain rapid measurements of coal temperature in mines, coal piles, coal bunkers, and other restricted spaces because of the complexities of these environments, bottlenecks in technology, and other factors.[32] A new coal fire detection technology is urgently needed to address this problem that is common in areas of the world where coal mining and/or storage exists.[33−36] In recent years, acoustic thermometry has been widely used in grain storage spaces, the atmosphere, and high-temperature industrial furnaces. The speed of sound in the propagation medium is the first function of the absolute temperature of the medium. The temperature field of a gas medium can be determined from the speed of the sound waves propagating through the medium. Measurements have high accuracy, cover a wide range of temperatures, can be made over large areas, do not require direct contact with the target, and are real time and continuous.[37−41] The mechanical properties, porosity, and other characteristics of loose coal in mines and bunkers are similar to those of stored grain; the loose coal is a porous medium formed by the free accumulation of coal bodies, which consists of two parts: coal blocks and voids.[4,5] Therefore, acoustic coal temperature measurement is expected to solve the problem of accurate detection in coal temperature of hidden fire sources from coal mining areas, provide the necessary conditions and theoretical basis for the development of coal spontaneous combustion detection technology, and

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realize the fine division in coal spontaneous combustion stages and the accurate prevention of control in coal mining areas as well as coal piles in coal bunkers, which is of great practical significance to the green, safe, and efficient coal mining in the world.

The author makes use of the idea of acoustic detection of the temperature field of the coal body in the mining area and coal pile bunker, constructs the mapping relationship between acoustic information and temperature field of the loose coal body, reveals the acoustic perception mechanism of the temperature field, and innovates the acoustic temperature sensing theory of the loose coal body. Reconstruction of the temperature fields in loose coal using experiments and numerical simulations contribute to our understanding of the characteristics of acoustic signals at the different stages of combustion. Development of noncontact technologies to detect high temperature areas in coal mines, piles, and bunkers contributes to the prevention and control of spontaneous combustion.

2. TECHNOLOGIES FOR THE MEASUREMENT OF COAL TEMPERATURE

2.1. Types of Temperature Measurement Technologies. In general, according to the criterion of contact between the measuring device and the object to be measured, the temperature measurement methods can be divided into two main categories: contact and noncontact temperature measurement methods.

The above contact temperature measurement is a direct contact between the sensor and the object to be measured, as well as a sufficient heat exchange between the two, and finally reaches the thermal equilibrium state, so that the temperature measurement can be achieved.[42,43] Common temperature testing methods include thermocouples,[44] thermal resistors,[45,46] and fiber optic pyrometers.[47−49] Direct contact technologies are simple, intuitive, and easy to use, and were the first ones to be developed. However, measurement errors are introduced by the direct contact between the sensor and the coal and by ambient temperature, as reaching thermal equilibrium takes time. As a result, real-time measurements cannot be made using these technologies, as sensors are in contact with harsh environments that are highly corrosive or at high temperature and pressure, sensor performance, and lifetime that are affected to varying degrees. As a result, there are measurement errors and potential maintenance work, and economic costs are high. Noncontact technologies acquire real-time temperature measurement by measuring temperature-related physical or chemical parameters and do not have the shortcomings of direct contact technologies. The noncontact temperature measurement method has less thermal inertia and better real-time performance, which is conducive to measuring the temperature situation of dynamically changing objects. Common temperature testing methods include infrared thermometers,[50,51] optical pyrometers,[52,53] and acoustic[36−40,54] and other methods.

Acoustic temperature measurements are an emerging technology in recent years. On the one hand, it can adapt to various harsh environments, including those that are highly corrosive, dusty, or at high temperatures, and on the other hand, it also has the advantages of continuous measurement of the measured object, high accuracy, wide range, and remote control. In coal mining areas or coal bunkers, the use of characteristics such as porous media of loose coal bodies and existing acoustic temperature measurement technology is expected to solve the problem of accurate detection of the temperature of hidden fire sources, which can provide new ideas and new methods for the perfection of coal spontaneous combustion detection technology.

2.2. Technologies for the Detection of Coal Spontaneous Combustion. Self-ignition of loose coal is an oxidative exothermic process, which releases large amounts of heat and gas and results in abnormal values in temperature, resistivity, magnetism, concentrations of radioactive radon and other gases, and other parameters in the overlying coal seam in the loosely packed coals; the parameter anomalies are used to obtain the temperature of coal spontaneous combustion region by using the correspondence between the variation pattern of these parameters and the temperature.[55] In recent years, coal spontaneous combustion detection techniques such as resistivity and remote sensing have been used to measure temperature and detect fires in coal mines (Table 1).[56−59]

Table 1 summarizes the advantages and disadvantages of various detection methods, and methods vary in their accuracy. Because of various complex factors, it remains difficult to obtain real-time measurements of temperature and guide fire rescue teams. However, unlike the methods described in Table 1, acoustic thermometry has the advantages of high accuracy, ease of use, and real-time data acquisition. Given the research and application of acoustic temperature measurement techniques on propagation laws, it provides the necessary conditions and theoretical basis for the research of acoustics in the field of coal spontaneous combustion detection in coal mining areas.

3. FIRE DETECTION USING ACOUSTIC THERMOMETRY

The spontaneous combustion of loose coal creates a solid−gas mixture in which the temperature field and gaseous products change continuously, which makes it difficult to obtain accurate measurements of spontaneously combusted coal.[60] In view of the basic principle of acoustic temperature sensing, the propagation decay rule of acoustic characteristics in the temperature field of spatial and temporal evolution, this paper uses the relevant theories and research in the fields of coal spontaneous combustion theory, acoustic theory, heat transfer and digital signals, etc., in order to develop an outlook on the evolution of combustion sound characteristics in the process of spontaneous combustion for loose coal bodies, the current status of "single source" and "dual source" acoustic temperature sensing technology for hidden fire sources. "Single-source" acoustic thermometry is a method that accepts only one acoustic signal source, the acoustic signal from combustion sound or an external acoustic emission device. The "Dual source" acoustic thermometry method accepts an acoustic signal generated by two independent sources; an external acoustic emission signal and a combustion signal combined into a new composite acoustic signal are accepted.

3.1. Principles of Acoustic Thermometry. The principle of acoustic temperature sensing mechanism is based on multipath time-of-flight (TOF) to solve the multidimensional temperature field distribution. Following the acquisition of the TOF and the discretization of the temperature field for each path, an algebraic equation representing the relationship between temperature and TOF in the discrete grid is established, transforming the temperature field reconstruction problem into a problem of solving a system of equations.[61,62] The propagation velocity of sound waves in a gas medium is a function of the gas temperature. Assuming that gas composition and content are

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Table 1. Selected Techniques Used for the Detection of Coal Spontaneous Combustion

classification	method	brief description	advantages	disadvantages
Underground	Magnetic techniques[29,30,41]	Analogous to the resistivity method, the spatial distribution of subsurface fire zones can be identified by observing changes in the magnetic field at the surface	High precision; large detection depth, adjustable to different detection scales	Time-consuming (ground-based measurements); expensive (airborne surveys); low sensitivity to coal spontaneous combustion phase; susceptible to interference from external magnetic signals
	Self-potential method[55,56]	Analyze the potential difference in the coal seam envelope to deduce the location and magnitude of the range of coal spontaneous combustion	Less cost-effective; higher accuracy; identification of active coal spontaneous combustion is easy	Time-consuming; detection range is limited; fragile to other currents
	Resistivity method[25,56,57]	Location of coal spontaneous combustion is deduced from the anomalous resistivity that appears in the coal seam envelope	Low cost-effectiveness; high accuracy	Waste of time; inability to delineate the area of spontaneous coal combustion; liable to the influence of natural factors such as topography
Ground	Surface temperature measurements[33,34]	Measured the temperature of the ground surface and deduced the specific location of coal spontaneous combustion	Low price; simple for operation	Timesaving; results are less accurate and more influenced by the terrain
	Isotopic radon thermometry[22,23]	Use the correlation between radon gas concentration and temperature to determine the range and depth of detecting coal spontaneous combustion	High resolution; suitable for different detection scales	High cost-effectiveness; sensitive to soil moisture, geological structure and topsoil thickness
Spaceborne	Spaceborne multispectral remote sensing[27,58]	Using satellite and carrier multispectral remote sensing to determine the location and extent of coal spontaneous combustion	Wide detection range; real-time monitoring available	high costs; prolonged time consumption; weather and other natural factors
	High spatial resolution remote sensing[28,59]	Installed onboard satellites with radar sensors for early prediction and range estimation of coalfield fires	Time-saving; widespread coverage for monitoring	No precision; expensive

known, the relationship between the propagation velocity of sound waves and the temperature is as follows:[63−68]

$$v = \sqrt{\frac{\gamma RT}{m}} = Z\sqrt{T} \tag{1}$$

where v is the speed of acoustic wave propagation in m/s; γ is the ratio of constant pressure specific heat capacity to constant volume specific heat capacity of the gas medium and is related to gas composition; R is the gas constant, which is 8.314 J/(mol·K); T is the thermodynamic temperature in K; m is the molecular weight of the gas in kg/mol; and Z is derived as follows:[68]

$$Z = \sqrt{\frac{\gamma R}{m}} \tag{2}$$

where Z is a constant Z of 20.03 for the given gas. Kong et al.[69] used a constant Z of 19.98 for the flue gas.

Assuming that there are M paths in the acoustic thermometry system and N cells in the temperature field, then y_i, which is the TOF of the wave in the ith acoustic range, can be derived as follows:

$$y_i = \int_{L_i} \frac{1}{v_j(x, y, z)}\, dl + n_i = \int_{L_i} f_j(x, y, z)\, dl + n_i \tag{3}$$

where L_i is the ith acoustic ray transmission path; (x,y,z) is the position of the pixel; $v_j(x,y,z)$ is the speed of sound of the jth pixel; $f_j(x,y,z)$ is the reciprocal of the speed of the jth pixel; and n_i is the measurement noise. A system of equations is obtained after each measurement cycle. Equation 3 can be expressed by the following matrix equation:

$$C = AF + n \tag{4}$$

where $A \in R^{M\times N}$ denotes the length of the line segment cut out of the jth pixel by the ith ray C; $C \in R^M$ is the measured TOF vector; $F \in R^N$ denotes the spatial state factor, which is the reciprocal of the velocity; M represents the total number of independent TOF measurements in the entire temperature field; N is the number of cells in the reconstructed spatial division; and $n \in R^M$ denotes the noise vector in the TOF measurements of the temperature field. Equation 4 is used to derive F, and temperature $T(x,y,z)$ can be obtained as follows:

$$T(x, y, z) = \frac{1}{F(x, y, z)^2 Z^2} \tag{5}$$

Based on the above basic formula, the least-squares method (LSM) is generally used to reconstruct the temperature field, the reconstructed field is useful for data visualization, but resolution is low at the edges. Liu et al.[70] and Ziemann et al.[71] improved the iterative reconstruction algorithm and developed the simultaneous iterative reconstruction technique (SIRT). The SIRT has improved convergence and stability but requires time-consuming iterative steps.

Shen et al.[72] and Jia et al.[73] reconstructed several classical temperature distribution models using multiple quadratic (MQ) radial basis function interpolation combined with LSM (LSM-MQ) and Markov radial basis function interpolation combined with LSM (LSM-MK), but the number of sub-blocks needs to be smaller than the number of ultrasonic propagation paths. To improve accuracy, Liu et al.[74] proposed an optimization algorithm called two-phase reconstruction method based on radial basis function approximation (RBFA). It could avoid the inversion process during the reconstruction and compensate for

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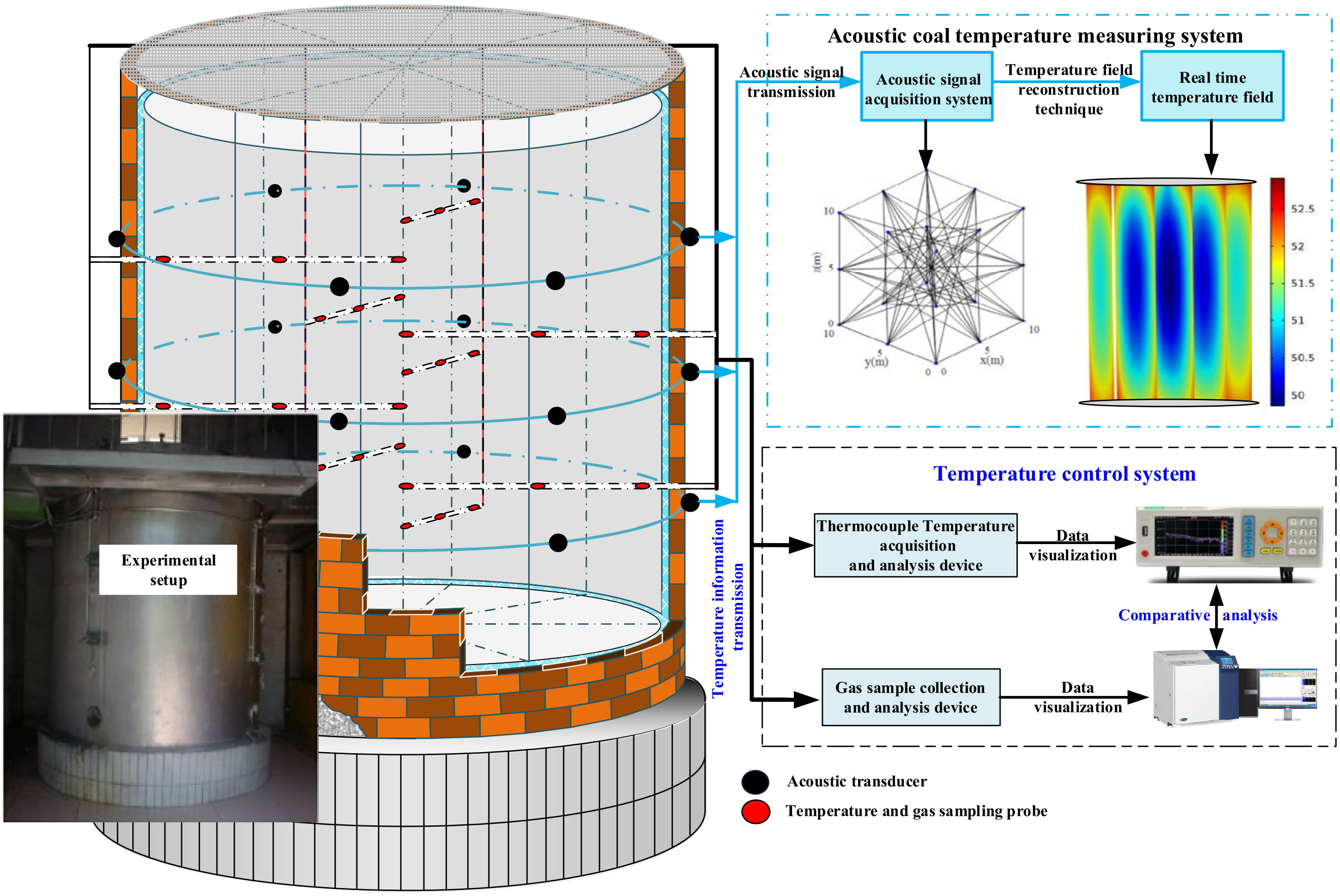

Figure 3. Principles of a coal acoustic thermometry system.

the loss of temperature information at the edge of the measurement area by LSM.[75] Inverse quadratic (IQ) functions are global radial basis functions that take many forms provided that there is little variation in the shape parameters. They are commonly used to solve convection−diffusion problems, which can be used to reconstruct the temperature field; results have high accuracy, but the process involves matrix inversion.[76,77] Singular value decomposition (SVD) is an algorithm commonly used in machine learning.[78] It can be used for feature decomposition in dimensionality reduction algorithms. Inverse quadratic functions can be used to fit sparse data with high accuracy, and SVD can be used to solve the matrix. Zhao et al.[79] combined IQ with SVD to solve the problem of matrix inversion in the reconstruction of the temperature field. They used a Gaussian distribution to model combustion noise during boiler operation and found that reconstruction results are strongly influenced by combustion noise. The different algorithms mentioned above all have their own limitations, but they will provide a basic theoretical and technical reference for the acoustic method to detect coal temperature, in order to construct a temperature field reconstruction technique suitable for acoustic coal temperature measurements and finally solve the problem of accurate coal temperature identification in the mining area.

Acoustic thermometry can be used to determine heat balance, combustion efficiency, energy consumption, and carbon emissions, and the temperature field can be reconstructed by optimizing the effective flight paths at a later stage. In the dynamic and evolutionary process of spontaneous combustion, it is necessary to acquire data on various acoustic signals, temperature, gas concentrations, and other parameters during the different stages of combustion. Figure 3 shows the principles of a coal acoustic thermometry system. The system includes a container in which spontaneous combustion takes place, an acoustic system, temperature field reconstruction, and other technologies. Study involves the propagation characteristics of acoustic waves in loose coal bodies with different temperatures and gas concentrations, followed by the establishment of suitable reconstruction methods based on the above different temperature field reconstruction algorithms, which can intuitively reflect the temperature changes at the site and realize the fine delineation and precise prevention and control of the coal spontaneous combustion stages in the mining area and coal piles and bunkers.

3.2. Single Source Acoustic Thermometry to Detect Fires in Loose Coal. Combustion or a sound emission device can be the sound source for single source acoustic thermometry. This paper investigates these two aspects based on the propagation characteristics of acoustic waves.

3.2.1. Characteristics of Combustion Sound from the Spontaneous Combustion of Loose Coal. In terms of the propagation characteristics of the sound waves to be measured that are emitted inside the area to be measured, the combustion sound is generated by the low frequency vibrations in the surrounding air medium excited upon molecular collisions from inside the heated object.[80] Combustion sound has the characteristics of sound waves, follows the propagation of sound waves, and has a large penetration depth and propagation distance.[81,82] Acoustic receivers can be used to distinguish combustion sound from other infrasonic waves in the environ-

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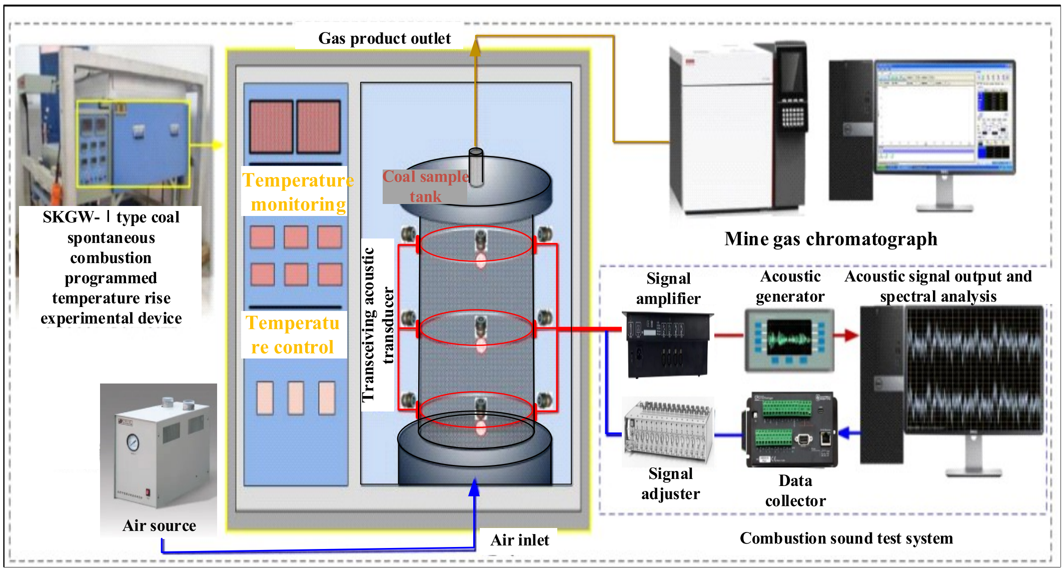

Figure 4. System for the study of the evolution of combustion sound from the spontaneous combustion of loose coal.

ment and identify the combustion sound produced by loose coal spontaneous combustion. Combining the principles of acoustics with the mechanism of spontaneous combustion, a robust theory can be elaborated to support the development of coal acoustic thermometry technologies.

Jiang[83] analyzed the mechanism of combustion sound generation. Following this principle, the author found that combustion sound can be approximated as a low-frequency shock signal and proposed a method to detect coal fires at an early stage. Infrasonic waves in the air surrounding the heated object are detected, and combustion sound is identified. Rong et al.[84] used acoustic meters to measure the combustion sound, and they derived the law of flame sound frequency, combined it with the existing law of flame pulsation frequency, and discussed some of the basic issues around pulsation and sound frequencies. Song et al.[85] proposed a sound generation mechanism for underground coal seam combustion, developed a method to characterize the infrasound emitted by spontaneously burning coal to obtain frequency characteristics varying with the material; combustion always generates infrasound. Therefore, acoustic temperature measurement technology could be applied to the detection and prevention of coalfield fires.

Figure 4 shows a system for the study of combustion sound in spontaneously combusting coal. The system includes an experimental device in which coal can be heated and spontaneous combustion can occur; an acoustic transceiver on the outside of the device records the sounds generated during combustion; signal amplifiers, data collectors, and other equipment are used for signal output and spectral analysis; the evolution of the combustion sound from loose coal spontaneous combustion is monitored and studied. Later, the experimental platform of acoustic emission for the spontaneous combustion in loose coal body is built, which can test and analyze the characteristics of acoustic emission signal so as to study the frequency change law of combustion sound signal in the stage from low temperature oxidation self-ignition in coal to complete combustion. Thereafter, the study should examine the evolution of different parameters of combustion sound signals (for example, frequency, amplitude of vibration, wave speed, and phase) under different conditions (for example, coal rank, temperature, particle size, and gas composition) to elucidate the key mechanisms and relationships between combustion sound and spontaneous combustion. In addition, the characteristics of combustion sound, the form of coal samples, the temperature of coal, gas composition, and other factors should be analyzed to reveal the principle of combustion sound generated during the fine division process in the spontaneous combustion for loose coal bodies, and finally the combustion sound signal characteristics of each stage change law should be launched to achieve the purpose of acoustic measurement of coal temperature.

3.2.2. Acoustic Thermometry Using External Sound Sources. Loose coal is usually regarded as a nonhomogeneous medium. Its spontaneous combustion is a dynamic process of changes in temperature and gas emissions.[1−3,16−19] The mixed solid−gas medium, the temperature field, and the gas emissions change constantly during coal combustion. The use of an external acoustic source signal device, combined with the distortion characteristics in the porous medium when the acoustic wave propagates within the distortion characteristics and attenuation law, provides a theoretical basis for the fine delineation of coal spontaneous combustion in the mining area acoustic temperature sensing technology.

An additional acoustic emission device during spontaneous combustion of loose coal bodies, the main use of acoustic signal propagation characteristics parameters and influencing factors, reveals phenomena such as the zigzagging of acoustic signals through the interstices in porous media. For example, Li et al.[86] reported that effective porosity and microporosity are strongly and positively correlated with pore maturity and negatively correlated with coal rank and acoustic wave velocity; the acoustic wave velocity is also susceptible to other factors such as the state and proportion of various substances in the coal; coal is a porous medium with a complex pore structure, which directly affects the spatial arrangement and acoustic wave velocity of the sample. Othmani et al.[87] treated the air gap as a rigid cylindrical tube and studied the effect of particle size, density, and stacking density on the propagation of acoustic waves through porous media. The greater the particle size, and the smaller the cylindrical tube density and stacking density. It is conducive to the propagation of sound waves within the porous medium. Loose coal is a mixed solid−gas medium and is often regarded as a porous medium in research studies. Yin et al.[88] and Gao et al.[89]

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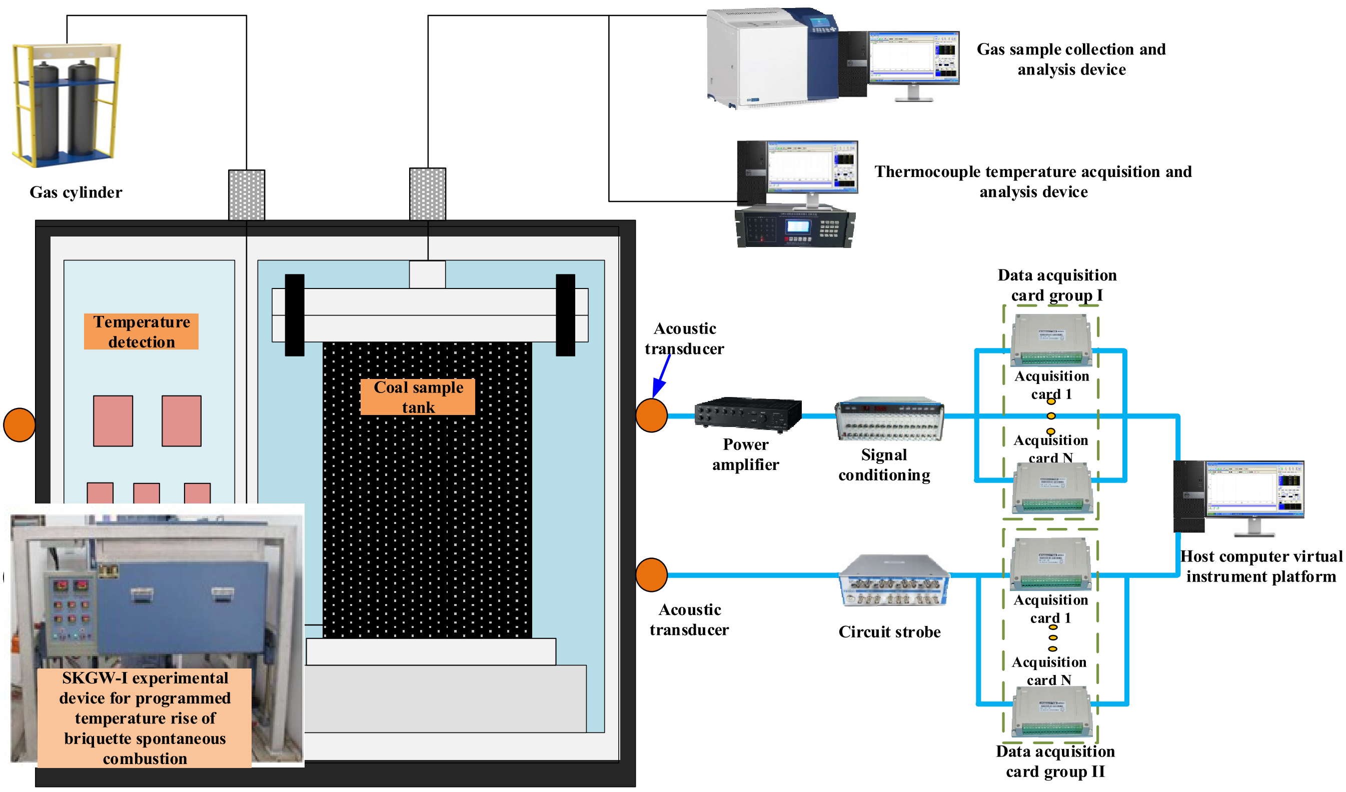

Figure 5. System for the study of the propagation of acoustic signals in loose coal using an external sound emission device.

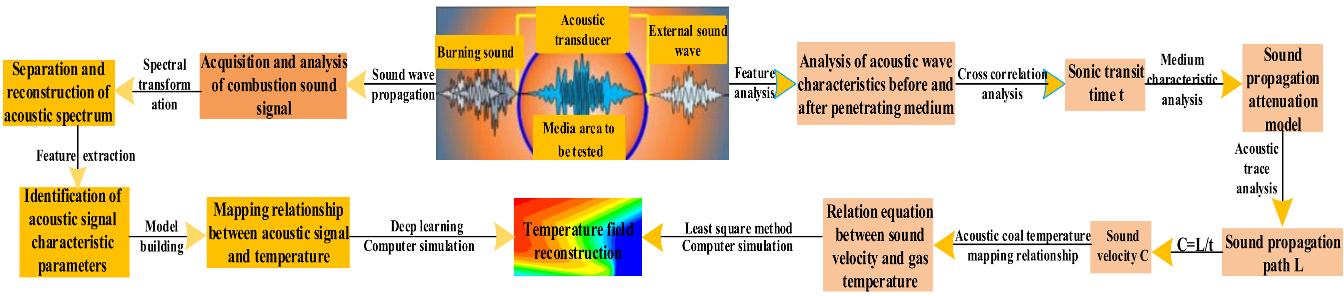

Figure 6. Principles of dual source acoustic thermometry to detect hidden fire sources in loose coal in mines.

found that the correlation between acoustic sequences suddenly decreased before rock damage and predicted rock destabilization under load. Lai et al.[90] and Li et al.[91] combined an infrared thermal imaging camera monitoring system with an acoustic emission system to study the evolution of the acoustic spectrum and distribution during the fracturing of coal rock. Sun et al.[92] analyzed the stability of hard rock columns between very steep and thick coal seams during four stages of a mining operation. They concluded that the thermal effects of the acoustic emission tests and infrared radiography can be used to characterize the physical properties of rock under high stress; in the later stages of the operation, the number of acoustic emissions increased, and energy was also released. In this paper, the aspects of acoustic emission signal propagation law associated with coal rock and the porous medium characteristics of the applied acoustic source signal device with loose coal body are studied, mainly using acoustic emission experiments to investigate the characteristic parameters and influencing factors of acoustic wave propagation within the coal rock body. These will provide theoretical and technical support for the acoustic method to detect coal temperature, developing a new method of detecting hidden fires in coal mines, in order to solve the problem of accurate identification of coal temperature in mining areas.

Figure 5 shows a system for the study of the propagation of acoustic signals in loose coal using an external sound emission device. It is used to determine the relationship between the speed of sound and the temperature of the medium and can form the basis for the development of coal acoustic thermometry technologies. The acoustic propagation model of loose coal body is constructed by applying acoustics and Biot's theory, combining with the Fermat principle to analyze the bending effect of a nonhomogeneous temperature field acoustic trajectory. It is proposed to study the main paths and equivalent path methods of acoustic propagation in the coal body, to construct the conversion relationship between sound velocity in air and the loose coal body, and to theoretically analyze the influence of temperature, particle size, pore morphology, gas composition, sound frequency, and other factors on them. At a later stage, combined with the research results of coal spontaneous combustion at the present stage, the experimental treatment uses the least-squares method to realize the grid, while constructing the multifactor relationship between temperature,

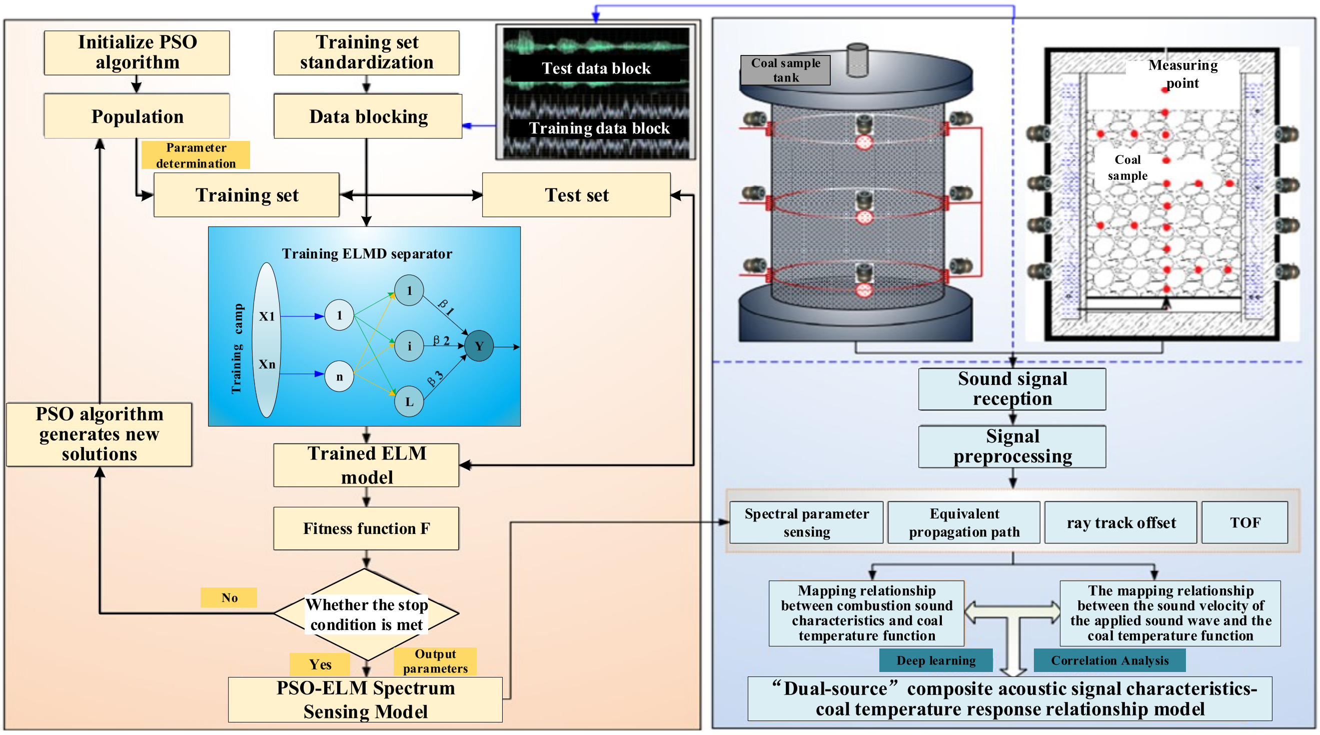

Figure 7. System for the study of the relationship between dual source composite acoustic signals and coal temperature.

gas composition, pore morphology, and sound velocity within the grid cell as a function; using MATLAB, sound velocity decay is simulated; the bending path of sound lines is simulated under the action from the temperature field, gas concentration field, and other factors; the experimental data are combined to modify the model of sound velocity-coal temperature function in loose coal; MATLAB simulation is used to optimize the algorithm to verify its construction; the dynamic response characteristics of acoustic signal versus coal temperature in porous medium are revealed. Finally, the correspondence principle between the fine division in each stage and the characteristic parameters for the acoustic signal is explained in the spontaneous combustion from the loose coal body in the mining area.

4. DUAL SOURCE ACOUSTIC THERMOMETRY TO DETECT FIRES IN LOOSE COAL

4.1. Dual Source Acoustic Thermometry. In the condition of an external sound source, the coal body spontaneous combustion itself to produce combustion sound can constitute the loose coal body hidden fire source "dual source" acoustic temperature sensing technology. Its technical research process is shown in Figure 6. Then, the research will focus on the characteristics of the acoustic signals, generation of combustion sound, evolution of the combustion process, and attenuation and propagation of the dual source composite acoustic signal in loose coal with increasing temperature. The experimental device will also be built to test the sensitivity of the system to coal temperatures and contribute toward the detection of hidden fire sources in coal.

Signal processing is an important part of dual source thermometry. Traditional signal analysis and processing techniques: with the acoustic signal from the time domain signal through the Fourier transform to the frequency domain, the signal waveform is described as a variable as frequency, reflecting the frequency and frequency domain of the signal. Prajna et al.[93] used a harmonic regenerative noise reduction (HRNR)-based Wiener filter to detect acoustic emission (AE) signals from noisy environments, and the HRNR technique can regenerate harmonics, overcome distortions that occur with overestimation of the conventional Wiener filter, and preserve the essential signal content of AE signals. Liang et al.[94] used wavelet transforms to amplify local characteristics in the time and frequency domains and found that processed signals can accurately reflect the frequency components of the original acoustic signals, the noise was eliminated effectively, but there are limitations to the application of wavelet and Fourier transforms to certain nonstationary and nonlinear signals.

Bao et al.[95] proposed a phase demodulation algorithm based on the Hilbert transform and constructed a new fiber optic distributed acoustic wave measurement system. The new algorithm could be used to correctly and stably demodulate the amplitude, frequency, and position of the applied sinusoidal signal and obtain accurate measurements of distributed vibration signals. Wei et al.[96] proposed a signal processing technique that combines traditional spectral subtraction with the Wiener filter. The transmission function of the Wiener filter was obtained from the signal-to-noise ratio; the snoring signal after spectral subtraction will further reduce the noise after passing through this filter, which performs well in sleep snoring noise processing applications. Acoustic signal recognition and processing technology are beginning to be developed in terms of theoretical fundamental research, which indicates the feasibility of acoustic thermometry has been proven, but there is as yet no report on the application of acoustic thermometry to loose coal.[97,98] In this paper, experimental tests on the acoustic emission of loose coal bodies are carried out at a later stage, and then the acoustic propagation characteristics of the composite effect between the burning sound and the applied acoustic waves in the process of coal spontaneous combustion are studied, and

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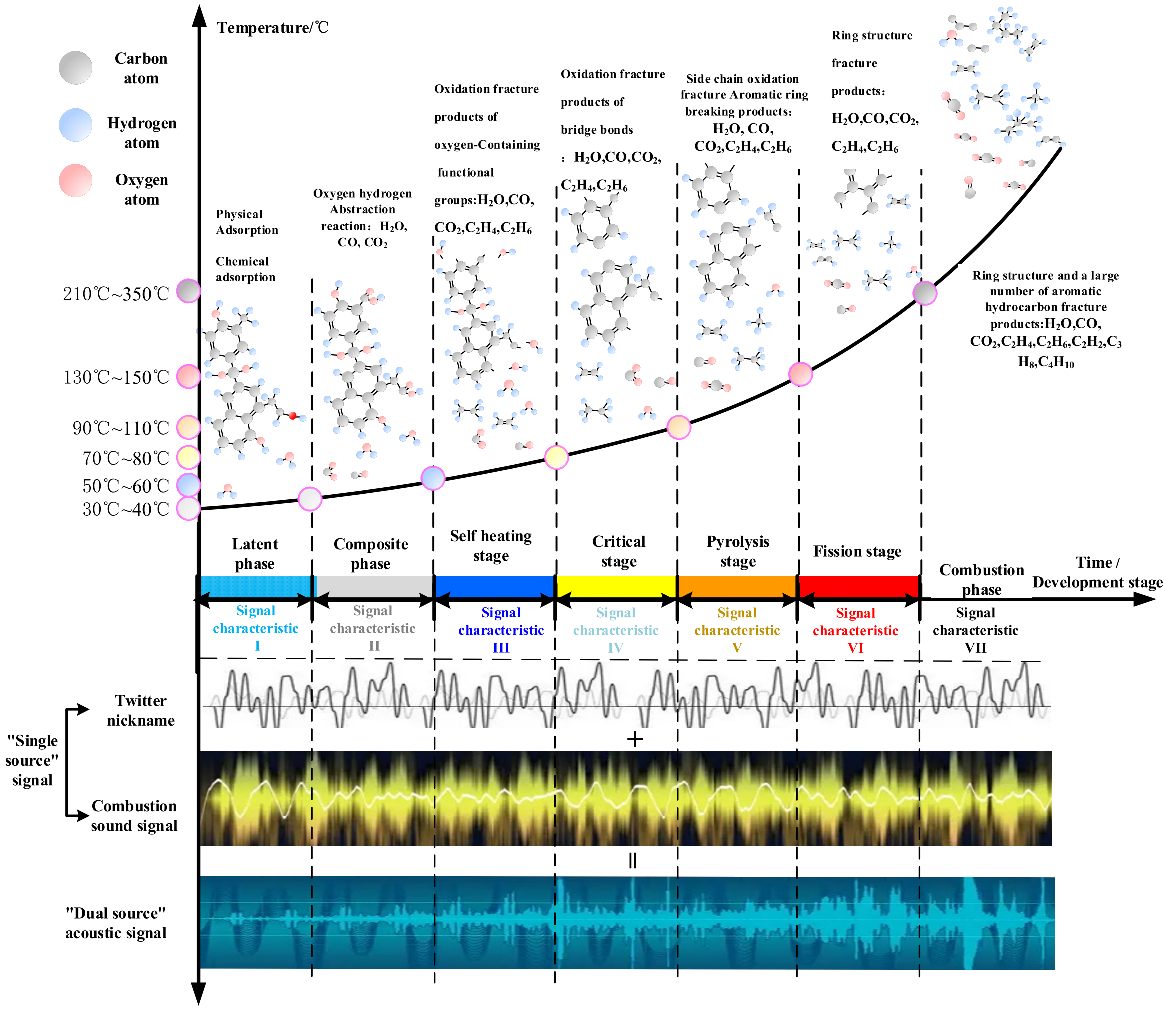

Figure 8. Dual source composite acoustic signals that correspond to different stages of the spontaneous combustion of loose coal.

the evolution characteristics for the key parameters of the superimposed acoustic waves are analyzed, in order to investigate the mutual disturbance law of the "dual-source" composite acoustic waves; the proposed acoustic wave decomposition filtering algorithm will be used to study the clutter filtering rules in combustion sound and background noise, to construct the spectral separation method between combustion sound and applied acoustic wave. Using Biot's theory and numerical simulations, the attenuation and propagation of externally applied acoustic waves in loose coal are studied, and the influence of coal properties, porosity, and other characteristics on key parameters of acoustic waves (for example, signal distortion, propagation distance, and TOF) is examined to contribute toward the development of acoustic thermometry technologies for the detection of the different stages of the loose coal spontaneous combustion.

In general, like all combustion processes, spontaneous combustion of coal generates sound, and the combustion sound can be used to detect combustion but also interferes with acoustic thermometry that uses external sound sources. On the basis of the evolution law of combustion sound in coal spontaneous combustion, the evolution characteristics of it with coal temperature are analyzed at a later stage, and then the evolution law of its characteristic parameters such as frequency, type, phase, and sound intensity are studied by the deep learning methods such as PSO particle swarm optimization, to extract the temperature change information for the accurate identification of combustion sound signals in each stage in loose coal spontaneous combustion. The mapping relationship between parameter of evolution and coal temperature functional is proposed to be constructed. The basic principle of temperature measurement is applied by the sound source, and the propagation speed of acoustic wave is affected by temperature and medium, and the experiments of adding acoustic wave to the loose coal body are carried out. The distortion characteristics of the acoustic signal and the trajectory law of the acoustic line when the acoustic wave propagates in the warmed loose coal body are analyzed. MALAB numerical simulation software is used to calculate the change of acoustic velocity in the warmed loose coal body and establish the mapping relationship between coal temperature and acoustic velocity. Deep learning methods and correlation analyses can be used to map the relationship between coal temperature and sound velocity. Figure 7 shows a system for the study of the relationships between coal temperature, combustion sound, and sound velocity for dual source composite acoustic signals. The application of single and dual source acoustic thermometry to identify hidden fires in loose coal in mines expands the field of application of acoustic thermometry. Accurate detection of spontaneous combustion

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contributes to improving the environmental safety and efficiency of coal mining and storage.

4.2. Mapping Acoustic Signal Characteristics to the Stages of Spontaneous Combustion. Combustion sound is nonlinear and nonsmooth, embedded in the background noise of the environment, and can be approximated as an impact signal. As the combustion process proceeds, the energy of the combustion sound is significantly higher than the background noise energy. Based on this principle, the experiments can separate and filter the combustion sound and noise signal, and get the evolution rules of combustion sound with coal temperature. The propagation of the applied acoustic wave is mainly affected by the temperature, gas conditions, particle size, and so on, in the loose coal body, using the applied acoustic wave devices emitting different frequencies to reduce the influence of these factors on what it can, and then getting the evolution law of the applied acoustic wave signal with coal temperature. Under the same experimental conditions, the experiments use the applied sound waves to measure the temperature in the loose coal body, due to the existence of combustion sound in the coal body and the superposition of the applied sound waves, forming a "dual source" composite sound waves, acoustic processing of them, and finally getting the "dual source" composite sound wave propagation with the evolution of the coal temperature law in the loose coal body. The acoustic signal superposition technique can be used, and the experimentally obtained combustion sound and the applied acoustic signal are constructed into a new composite acoustic wave, while the gas concentration is detected by gas chromatography and compared with the acoustic signal of the "dual-source" composite acoustic wave in the loose coal body. Finally the correspondence between the precise stages of coal spontaneous combustion and the acoustic signal characteristics of different stages is found. Figure 8 illustrates the mapping of acoustic signal characteristics to the stages of coal spontaneous combustion using experiments with combustion sound and externally applied acoustic signals. In the future, the mentioned device will need to be improved by adding materials such as sound and heat insulation so that the effect of echoes on the experiment can be reduced. The new composite acoustic wave can be used to accurately detect hidden fire sources in coal mines, piles, and silos, and support the development of new technologies and equipment for the prevention and control of coal spontaneous combustion.

5. CONCLUSIONS

(1) The combustion sound of loose coal spontaneous combustion in the mining area has an important relationship with a series of influencing factors such as the degree of coal metamorphosis, coal temperature, void characteristics, and gas conditions. However, it will be the development trend in acoustic coal temperatures measurement to make a corresponding relationship model based on these conditions with the acoustic signals.

(2) Combustion sound and externally applied sounds can combine to form a dual source composite acoustic wave. The effects of superposition and mutual interference of the source waves on the waveform and characteristics of the composite wave are unclear. The use of dual source acoustic thermometry is limited by our ability to separate the composite wave spectrum and understand the effects of coal properties and gas composition. Biot theory and acoustic principles combined with numerical simulation in order to study the attenuation rules of the applied sound source in loose coal and coal temperature mapping relationship are another development trend of acoustic coal temperature measurement.

(3) In the acoustic signal processing, the mapping response relationship between single-source and dual-source acoustic waves and coal temperature in coal spontaneous combustion is not clear, and so on. The evolutionary relationship between multiple factors such as correlation analysis combustion sound and applied acoustic waves, coal sample, coal temperature, and gaseous product composition is used to derive an algorithm applicable to the analysis of acoustic signals in spontaneous combustion of loose coal bodies; knowledge of acoustic signal characteristics at the different stages of combustion could be employed to prevent and control spontaneous combustion. Accurate detection of spontaneous combustion contributes to the environmental safety and efficiency of coal mining and storage.

AUTHOR INFORMATION

Corresponding Authors

Haoyu Shang − *College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China; Key Laboratory of Western Mine and Hazard Prevention, Ministry of Education of China, Xi'an 710054, China*; Email: 21220226114@stu.xust.edu.cn

Guobin Cai − *College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China; Key Laboratory of Western Mine and Hazard Prevention, Ministry of Education of China, Xi'an 710054, China*; orcid.org/0000-0002-9558-9043; Email: 19220214086@stu.xust.edu.cn

Authors

Jun Guo − *College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China; Key Laboratory of Western Mine and Hazard Prevention, Ministry of Education of China, Xi'an 710054, China*

Yongfei Jin − *College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China; Key Laboratory of Western Mine and Hazard Prevention, Ministry of Education of China, Xi'an 710054, China*

Kaixuan Wang − *College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China; Key Laboratory of Western Mine and Hazard Prevention, Ministry of Education of China, Xi'an 710054, China*

Shuai Li − *College of Safety Science and Engineering, Xi'an University of Science and Technology, Xi'an 710054, China; Key Laboratory of Western Mine and Hazard Prevention, Ministry of Education of China, Xi'an 710054, China*

Complete contact information is available at:
https://pubs.acs.org/10.1021/acsomega.3c00199

Notes

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