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Coal and Gangue Active Identification Method Using Microwave Irradiation-Infrared Detection

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Abstract: In the process of the longwall top coal caving method, automatic distinction between coal and gangue at the working face is one of the most critical factors for the success of the operation. An active coal and gangue identification method using microwave irradiation combined with infrared detection is proposed in this paper. Coal and gangue are irradiated with microwave to actively enhance the external differences between them, and then the quantitative data of the difference are quickly collected by a noncontact infrared thermal imager, to perform identification of coal and gangue. Using theoretical analysis and laboratory experiments, the physical and chemical properties of coal and gangue are analyzed in order to reveal the thermal sensitivity of coal and gangue to microwave irradiation. The influences of the coal and gangue particle size, microwave irradiation time and microwave frequency on the thermal sensitivity to microwave irradiation are investigated. The experimental results show that the average temperature rise in coal is approximately 1.5 times that in gangue material under the same microwave irradiation conditions. This supports the feasibility of this identification method, and provides theoretical and experimental bases for achieving rapid and accurate identification of coal and gangue in top coal caving operations.

Keywords: longwall top coal caving; coal and gangue identification; microwave irradiation; infrared detection; active method

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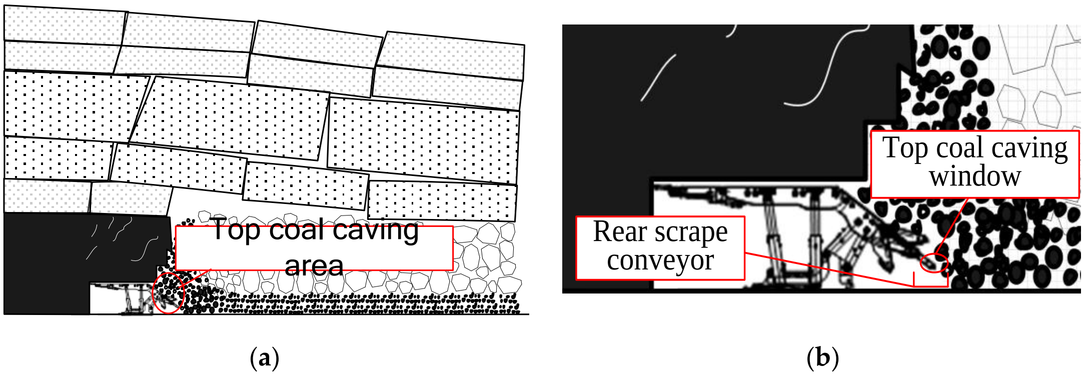
1. Introduction

Research on coal and gangue identification technology is mainly concentrated in the world's major coal-producing countries, such as the United States, Britain, Russia, China, and other countries. To date, more than 30 methods for coal and gangue identification have been developed. These include γ-ray radiation, radar detection, infrared radiation, pressure sensing, acoustic signal analysis, vibration signal analysis, image recognition, etc. [1–7]. Such detection methods are primarily passive; they identify differences between coal and gangue based on their chemical composition, physical characteristics, appearance color and signal of the hydraulic support tail beam. Due to the harsh environment of the underground longwall top coal caving (LTCC) working face, poor visibility, and external environment and equipment noise interference, previous coal and gangue identification methods in the field have yielded mostly unsatisfactory experimental results [8–16]. For thick coal seams, the longwall shearer cannot be used to mine the full seam thickness. Therefore, it is necessary to use the shearer to mine the lower portion of the coal seam, and the remaining upper coal seam is recovered by caving from the rear side of the shield as illustrated in Figure 1. When the top coal window is opened, caving begins with coal falling first onto the scrape conveyor, eventually followed by gangue. When the amount of falling gangue is deemed large, the top coal caving window is closed to stop gangue accumulation on the conveyor.



(**a**) (**b**)

Figure 1. Schematic diagram of LTCC working face. (**a**) Top coal caving area; (**b**) Enlarged top coal caving area.

As a result, coal and gangue identification has always been a technical difficulty in LTCC mining. Therefore, it is necessary to explore new and reliable automated coal and gangue identification methods.

According to the characteristics of microwave material heating and infrared thermal image recognition, such as selectivity, instantaneity, noncontact and strong anti-interference ability, coal and gangue have large thermal sensitivity differences under microwave irradiation, and infrared thermal imager can transform invisible infrared energy from objects in a certain area into visible thermal images in real time. Thus, an active coal and gangue identification method based on microwave irradiation and infrared detection is proposed. In this method, microwave irradiation is used to increase the external difference between coal and gangue, and then, noncontact infrared thermal imager is used to obtain the quantitative data of the difference instantly. The data obtained through comparative analysis are used for identification of coal and gangue. The merits of this method are that it is not affected by light or noise and does not require optical visibility. It is shown that the new method improves the applicability, instantaneity and accuracy of coal and gangue identification, and provides a new technical approach for coal and gangue identification.

2. Microwave Absorption Mechanism of Materials

The rock medium is composed of polar molecules and nonpolar molecules. Polar molecules easily form dipoles in an alternating electric field, and the polarization direction of dipoles is always consistent with the field strength direction of the alternating electric fields. Under microwave irradiation conditions, the polar molecules in the rock medium rotate in the high-speed alternating electric field, which must overcome the Van der Waals force between the internal dielectric molecules, generating heat by violent friction. The energy conversion entails transfer of the electromagnetic energy of the alternating electric field into the rock, while the macroscopic response is that the temperature of the rock rises [17–19].

Under microwave irradiation, the increase in the material temperature mainly depends on the heat absorption and dissipation. However, the exchange of heat is very complex. To simplify the problem, the following idealized assumptions are made for heating of a material by microwave irradiation. First, it is assumed that the energy in the heating system only comes from the microwave source. The energy output is assumed to be mainly dissipated into the microwave cavity through heat conduction of the container wall. Radiation and convection are considered to be the main causes of energy loss. Finally, the hypothesis that the initial and final temperatures of the material and container wall are the same is adopted [20].

Knowing that the mass of the rock medium is m, the specific heat capacity is C, the surface area is A, and the volume is V, the microwave energy absorbed by the rock medium during time Δt is Q.

$$Q = 2\pi f V \varepsilon_0 \varepsilon' tan\delta |E|^2 \Delta t \tag{1}$$

The calculation equation of the heat transfer Q_1 from the rock medium to the container wall is as follows.

$$Q_1 = K_1 A_1 (T_m - T_n) \tag{2}$$

where f—microwave frequency, Hz; ε_0—absolute permittivity of vacuum; ε'—real part of the dielectric constant of the material; $tan\delta$—tangent of the dielectric loss angle, indicating the efficiency of the material in converting absorbed microwave energy into internal energy; E—effective electric field strength of the material, V/M; K_1—heat transfer coefficient between the container wall and material; A_1—contact area of the material, m^2; T_m—final temperature of the material, °C; and T_n—initial temperature of the container wall, °C.

From the above assumptions, the temperature change Δt of the material during the whole microwave heating process is,

$$\Delta T = T_m - T_n \tag{3}$$

Therefore, the net energy Q_2 absorbed by the material in any time Δt is,

$$\begin{aligned} Q_2 = Q - Q_1 &= 2\pi f V \varepsilon_0 \varepsilon' tan\delta |E|^2 \Delta t - K_1 A_1 (T_m - T_n) \\ &= 2\pi f V \varepsilon_0 \varepsilon' tan\delta |E|^2 \Delta t - K_1 A_1 \Delta T \end{aligned} \tag{4}$$

and,

$$Q_2 = Cm\Delta T \tag{5}$$

Combining Equations (4) and (5), and simplifying leads to,

$$\frac{\Delta T}{\Delta t} = \frac{2\pi f V \varepsilon_0 \varepsilon' tan\delta |E|^2}{Cm + K_1 A_1} \tag{6}$$

Without considering the heat radiation loss and heat diffusion, Equation (6) can be simplified as follows.

$$\frac{\Delta T}{\Delta t} = \frac{2\pi f V \varepsilon_0 \varepsilon' tan\delta |E|^2}{Cm} = \frac{2\pi f \varepsilon_0 \varepsilon' tan\delta |E|^2}{C\rho} \tag{7}$$

where ρ is the density of the material in kg/m^3.

Equation (7) shows that the heating rate of the material is related to the parameters E, m, ε'. Different materials have different microwave absorption capabilities.

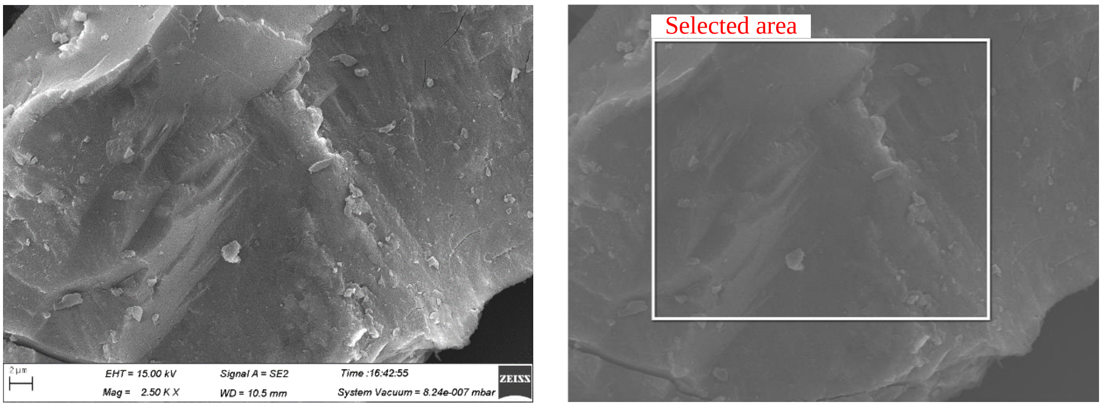
To explore the difference between coal and gangue under microwave irradiation, a scanning electron microscope, an X-ray instrument and a laser thermal conductivity analyzer were used to determine the element characteristics, mineral composition and dielectric constant of coal and gangue.

3. Microwave Absorption Tests

3.1. Analysis of Coal and Gangue Elements

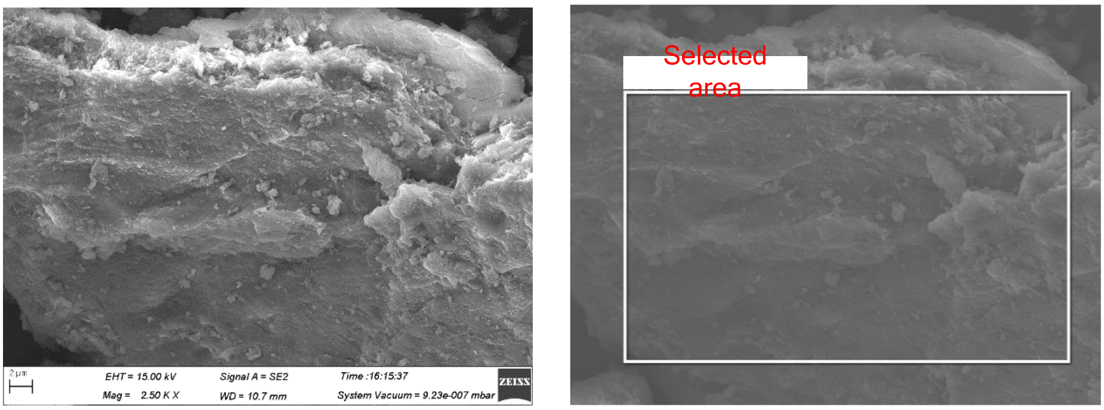
To analyze the composition of the main chemical elements in coal and gangue, a Zeiss Merlin compact field emission scanning electron microscope (SEM), produced by Carl Zeiss, from NY US, was used to carry out SEM tests, and test samples were collected at the 8202 LTCC working face of the Tongxin Coal Mine in the Datong coal field of China.

In the element characteristic analysis test of coal and gangue, first, test sample particles with good conductivity are selected by using the scanning electron microscope, the magnification is adjusted, and the focus is adjusted until the particles are clearly visible, as shown in Figures 2a and 3a. The magnification selected in the test is 2500 times. After the test particles are selected, the area to be analyzed is delineated by an energy dispersive X-ray spectrometer, as shown in Figures 2b and 3b. After the analysis area is delineated, the system automatically analyzes the element distribution in the delineated area, as shown in Figures 4 and 5. It can be concluded that the main constituent elements in coal and gangue are carbon, oxygen, aluminum and silicon.



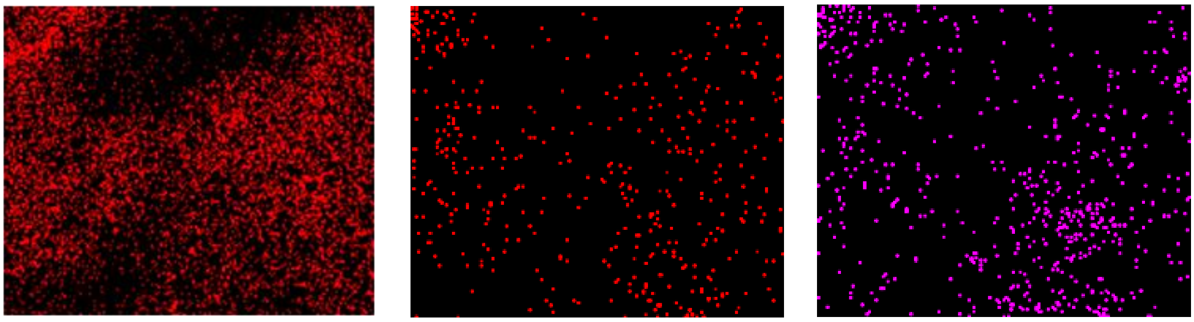
(**a**) (**b**)

Figure 2. Characteristic test of a coal sample element. (**a**) Morphological characteristics of coal sample; (**b**) Area selected to be analyzed by X-ray energy spectrum.



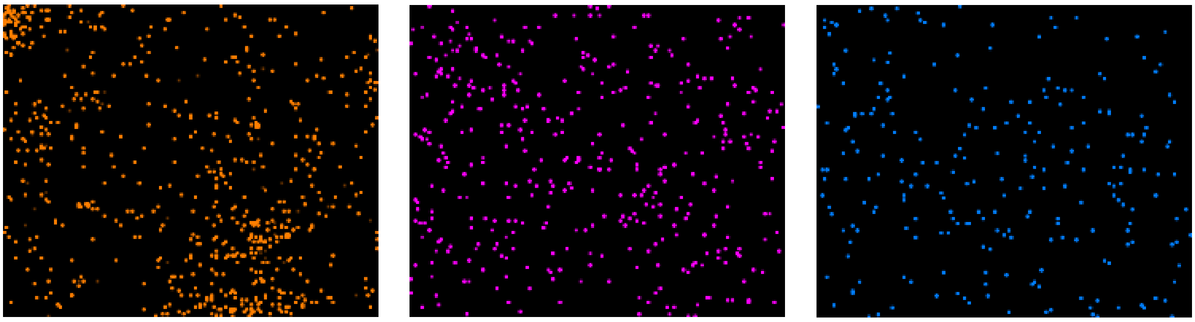
(**a**) (**b**)

Figure 3. Characteristic test of a gangue sample element. (**a**) Morphological characteristics of gangue sample; (**b**) Area selected to be analyzed by X-ray energy spectrum.



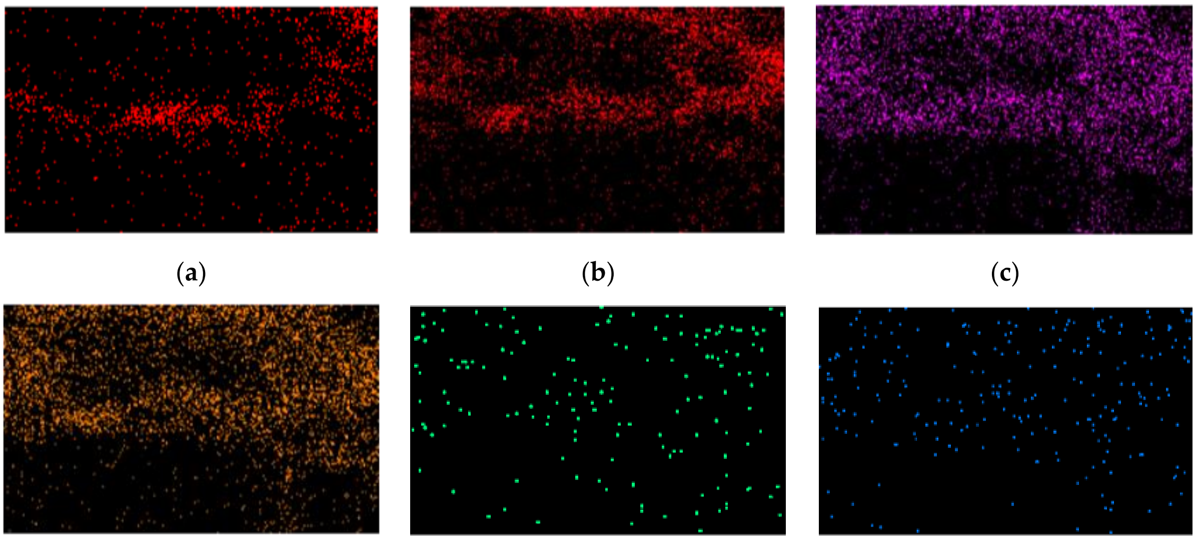
(**a**) (**b**) (**c**)

Figure 4. *Cont.*



(**d**) (**e**) (**f**)

Figure 4. Distribution map of main elements in coal samples. (**a**) Carbonel element; (**b**) Oxygen element; (**c**) Aluminum element; (**d**) Silicon element; (**e**) Sulfur element; (**f**) Phosphorus element.



(**a**) (**b**) (**c**)

(**d**) (**e**) (**f**)

Figure 5. Distribution map of main elements in gangue samples. (**a**) Carbonel element; (**b**) Oxygen element; (**c**) Aluminum element; (**d**) Silicon element; (**e**) Kalium element; (**f**) Phosphorus element.

The percentage comparison of the constituent elements in coal and gangue is shown in Figure 6. The content percentage of carbon, oxygen, silicon and aluminum in coal and gangue are quite different. The atomic percentage of carbon in coal reaches 90.8%, and the weight percentage reaches 86.4%. The atomic percentage of carbon in gangue reaches 44.5%, and the weight percentage reaches 32.8%. The content of carbon in coal is more than 2 times that in gangue. The total content of oxygen, silicon and aluminum in gangue is more than 3 times that in coal. This shows that the types of constituent elements in coal and gangue are basically the same, but the contents of the main elements are quite different. Coal is mainly composed of carbon and oxygen, and the proportion of carbon is approximately 85%. Gangue is mainly composed of carbon, oxygen, silicon and aluminum, with carbon accounting for approximately 30% and oxygen accounting for approximately 38%. The content of carbon in coal is much higher than that in gangue, and the content of oxygen, silicon and aluminum in gangue is much higher than that in coal.

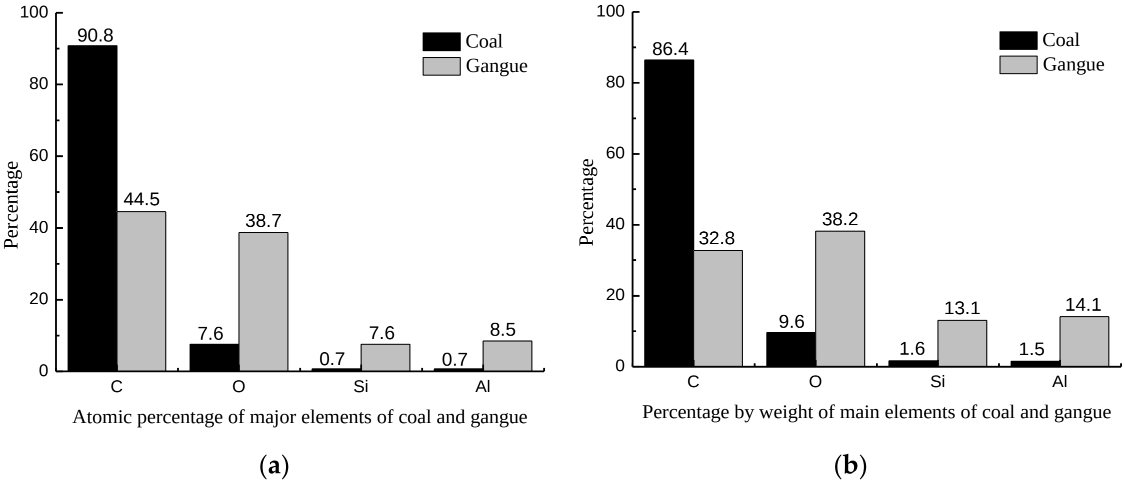
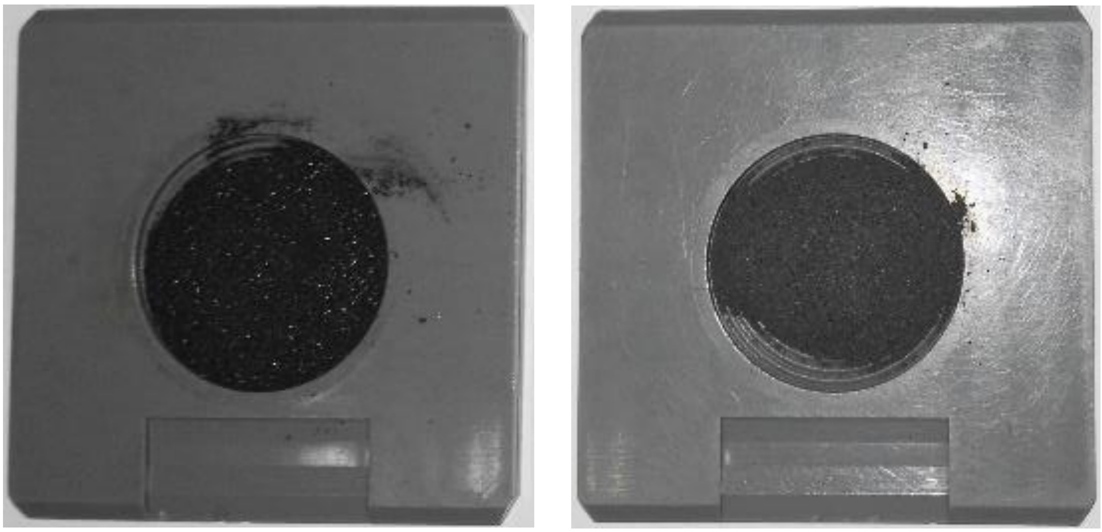


Figure 6. Comparison of test results of main elements content of coal and gangue samples. (**a**) Atomic percentage; (**b**) Percentage by weight.

3.2. Analysis of the Mineral Composition of Coal and Gangue

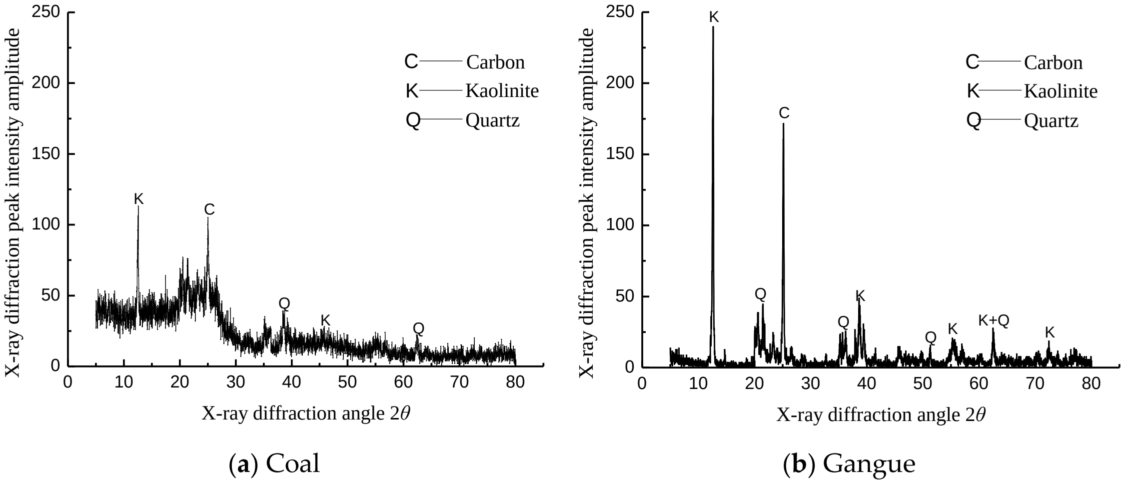
A D8 Discover X-ray instrument produced by Bruker in Germany is used to analyze the mineral composition characteristics of coal and gangue, and the differences in the coal and gangue compositions are compared. Appropriate amounts of collected coal and gangue samples are ground into powder and dried in a mortar, and then placed in a special sample carrier tank for the test, as shown in Figure 7. The samples are uniformly pressed into shape by the back pressure method and placed on the X-ray diffractometer stage for testing.



(**a**) Coal (**b**) Gangue

Figure 7. X-ray diffraction test sample.

After the test sample is scanned by the X-ray diffractometer, the spectrum is automatically generated. The components in the test sample are calibrated according to a standard sample, as shown in Figure 8. The results show that the main component of coal is carbon, accounting for more than 90%, with small amounts of kaolinite and quartz. The main components of gangue are carbon, kaolinite and quartz. The carbon content is approximately 40%, and the total content of kaolinite and quartz is approximately 50%.



(**a**) Coal (**b**) Gangue

Figure 8. X-ray diffraction test results of coal and gangue samples.

3.3. *Physical Property Test of Coal and Gangue*

To explore the differences in the heating rate and microwave absorption capacity of coal and gangue, the specific heat capacity and dielectric constant of coal and gangue under microwave irradiation are measured by a laser thermal conductivity analyzer and a vector network analyzer, respectively.

The specific heat capacity of a material refers to the energy released or absorbed by the material at unit temperature per unit mass, indicating the heat dissipation or heat absorption capacity of the material. To analyze the ability of coal and gangue to convert the absorbed microwave energy into thermal energy under microwave irradiation, an LFA 457 laser thermal conductivity analyzer is used.

3.3.1. Sample Preparation

To determine the specific heat capacity of solid materials with a laser thermal conductivity analyzer, it is necessary to process the test materials into small slice samples of φ12.5 mm (±0.05 mm) × 2.5 mm (±0.05 mm). To ensure the accuracy of the test sample size, the test sample is first crushed into powder, the measured powder sample of a certain quality is poured into a special φ12.5 mm compression molding device, and the poured powder sample is pressed into small thin pieces for testing under a pressure of 100 MPa. The densities of the obtained coal and gangue samples are 1.207 g/cm^3 and 2.153 g/cm^3, respectively. Three samples of coal and gangue are prepared, as shown in Figure 9.

Figure 9. Preparation of coal and gangue samples for specific heat capacity test.

3.3.2. Test Parameter Setting

The prepared coal and gangue samples are placed on the test instrument loading platform, and the basic information of the test is set. The models used in the test are Capel models with pulse correction. The laser voltage used is 1634.0 V, LFA 457 Medium Rg furnace body, and LFA 457 laser, produced by NETZSCH company, from Bavaria, Germany, a Std SiC 12.7 mm centering cone, argon filling gas, and a 60.00 mL/min flow rate. The experimental results show that the specific heat capacity of coal and gangue at 26.4 °C is 1.292 J/(g·K) and 1.002 J/(g·K), respectively.

3.4. Electrical Parameter Test of Coal and Gangue

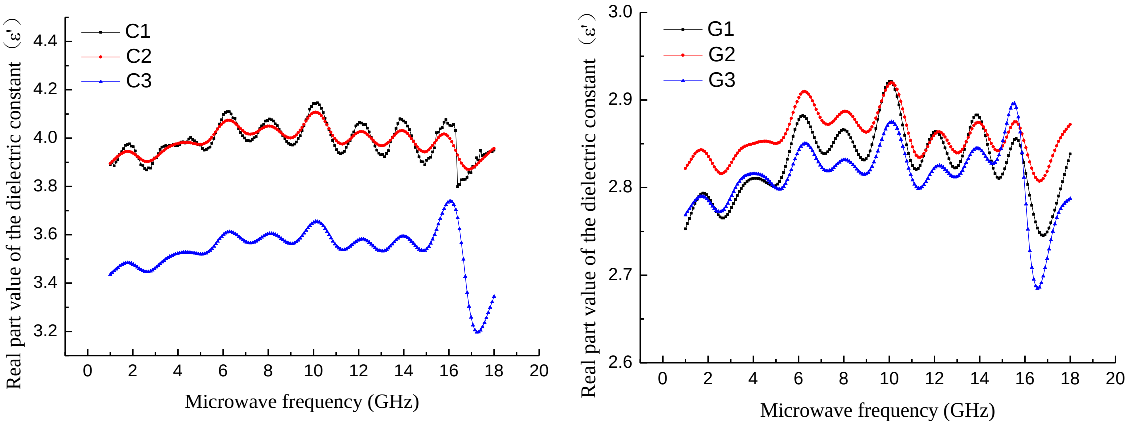
The dielectric constant and dielectric loss tangent of the material have the greatest influence on the microwave absorption ability. To explore the difference in microwave absorption ability between coal and gangue, an Agilent N5225A vector network analyzer, produced by Agilent Technologies company, from CA US, is used to test the dielectric constant and dielectric loss tangent of coal and gangue. The test frequency is 1.0–18.0 GHz, and the test temperature is room temperature.

Three types of coal and gangue powder samples with different particle sizes are obtained by passing the prepared coal and gangue powder through sieves with diameters of 0.25 mm, 0.18 mm and 0.075 mm from top to bottom, namely S1 < 0.075 mm, 0.075 mm < S2 < 0.18 mm, and 0.18 mm < S3 < 0.25 mm. According to the particle size range from small to large, the obtained coal and gangue particles are marked as C-1, C-2, C-3, G-1, G-2 and G-3 (C indicates coal and G indicates gangue).

The prepared coal and gangue particles and paraffin wax of different sizes are mixed according to a mass ratio of 1:1, and in a water bath at approximately 70 °C, the particle powder and molten paraffin of equal mass are mixed evenly. The liquid sample is poured into a prefabricated mold with an inner diameter of 3.0 mm, an outer diameter of 7.0 mm, and a height of 3.0 mm for compaction. After the sample is solidified, the mold is released. The test sample preparation process and a prepared sample are shown in Figure 10.

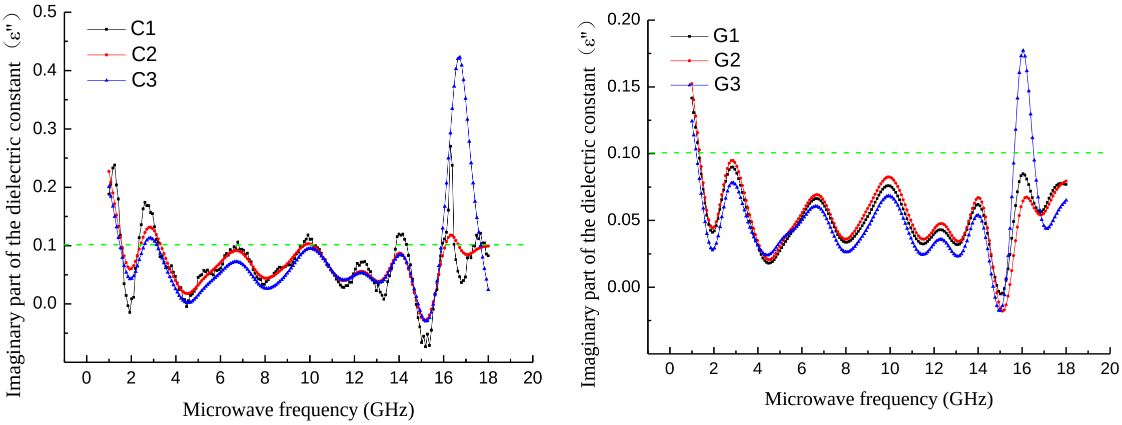
Figure 10. Preparation of coal and gangue samples for electrical parameters.

Under the same test environment and equipment setting conditions, the electrical parameters of 6 samples of coal and gangue are tested according to the dielectric constant measurement method. The test results are shown in Figures 11 and 12. The larger the real and imaginary parts of the dielectric constant of the material are, the stronger the material's ability to absorb microwaves and convert microwave energy into internal energy. That is, under the condition of microwave irradiation, the larger the real and imaginary parts of the dielectric constant of the material are, the more the internal energy is increased. In this experiment, the real part of the dielectric constant of coal samples with different particle sizes under microwave irradiation of 1.0–18.0 GHz ranges from 3.2 to 4.2, and decreases with increasing particle size, as shown in Figure 11a. The real part of the dielectric constant of gangue samples is 2.7–2.9, the correlation between the test results of gangue samples and particle size is small, and the difference among the three sets of experimental results is small, as shown in Figure 11b.



(**a**) Coal (**b**) Gangue

Figure 11. Change of dielectric constant real part for coal and gangue samples under different particle sizes.



(**a**) Coal (**b**) Gangue

Figure 12. Change of dielectric constant imaginary part for coal and gangue samples under different particle sizes.

Figure 12a shows that the imaginary part of the dielectric constant of coal samples shows a decreasing trend with increasing particle size, and several characteristic peak frequencies are: 2.65 GHz, 6.69 GHz, 9.97 GHz, and 14.09 GHz and 16.66 GHz. The peak value of the imaginary part of the dielectric constant of coal samples is mostly above 0.1. In Figure 12b, the variation trend of the imaginary part of the dielectric constant of gangue samples with particle size is not obvious, and there is little difference among the three groups of experimental data, in which several characteristic peak frequencies are 2.81 GHz, 6.65 GHz, 9.97 GHz, 14.09 GHz and 16.08 GHz. The peak value of the imaginary part of the dielectric constant of gangue samples is approximately 0.075.

3.5. Feasibility of the Microwave Irradiation-Infrared Detection Method

According to the laboratory SEM results, the main element component of coal is carbon, accounting for 86.4%; the main element component of gangue is oxygen, accounting for 38.2%, followed by carbon, accounting for 32.8%. The weight percentage of carbon in coal is 2.6 times that in gangue. The X-ray diffraction test results show that the main component of coal is organic matter mainly composed of carbon, and the main components of gangue is kaolinite and quartz, which contain some organic matter. The above results suggest that there are more polar molecules in coal than in gangue, and the number of polar molecules determines the material’s ability to absorb microwaves.

The electrical parameter test results show that the peak value of the imaginary part of the dielectric constant of coal is above 0.1, and that of gangue is approximately 0.075. The specific heat capacity of coal measured in the laboratory is 1.292 J/(g·K) at 26.4 °C. The corresponding specific heat capacities of gangue at the same temperatures is 1.002 J/(g·K). The resulting ratios of the specific heat capacities of coal and gangue samples is 1.29 at 26.4 °C. Ignoring the environmental heat exchange loss, the above parameters obtained in the laboratory are substituted into Equation (7). It can be estimated that the ability of coal to absorb microwaves is 1.3 times that of gangue.

Based on the specific heat capacity test of coal and gangue in the laboratory, the specific heat capacity of coal is slightly larger than that of gangue at lower temperatures, but with the rise in sample temperature, the specific heat capacity of coal is smaller than that of gangue. According to the average values of the specific heat capacities of coal and gangue between 26.3 °C and 34.6 °C, the average temperature rise of coal is 1.15 times that of gangue under the condition of absorbing the same energy. It can be concluded that the temperature change rate ratio of coal and gangue under the same microwave irradiation and irradiation time is approximately 1.5, which indicates that coal and gangue can show a large temperature difference under microwave irradiation. Under lower temperature conditions, as the temperatures of coal and gangue increase, the ratio of the rates of temperature increase of coal and gangue increases, and the temperature difference between coal and gangue after microwave irradiation is more obvious. Therefore, it is theoretically feasible to use microwave irradiation to actively increase the difference between coal and gangue.

4. Experiment of Microwave Irradiation of Coal and Gangue

As previously explained, the method of using microwave irradiation to actively increase the difference between coal and gangue is theoretically feasible, and laboratory tests are used to explore the specific differences between coal and gangue under microwave irradiation. Thermal sensitivity tests of coal and gangue under different particle sizes and microwave irradiation times are carried out, and the difference is obtained by an infrared thermal imager for analysis, to verify whether the microwave irradiation-infrared detection coal and gangue identification method is practical. The experiment is carried out in the Geomechanics Laboratory of McGill University. The main instruments used in the experiment are a microwave oven (Panasonic 800 W 2.45 GHz), an infrared thermal imager (Fluke TiS60), a mechanical vibrating screen device, a set of steel wire screens, a high-precision electronic platform scale, a cooling fan, etc. It should be noted that theoretically, the higher the microwave frequency, the greater the difference in thermal effect of coal and gangue. However, in this study, only one microwave emission frequency is used. The test materials mainly include a sample tray, a sample spoon, a glass box, a 5 mm thick cork plate (the cork plate has a good heat insulation effect to reduce heat conduction between the test sample and glass box), a plastic cylinder with an inner diameter of 100 mm, etc. Some of the test materials are shown in Figure 13.

Figure 13. Accessories for microwave irradiation test.

4.1. Sample Preparation

The original coal and gangue samples are crushed and screened on the mechanical vibrating screen to prepare four kinds of coal and gangue particle sizes, i.e., 1.40 mm < S4 < 4.75 mm, 0.60 mm < S3 < 1.40 mm, 0.30 mm < S2 < 0.60 mm, and S1 < 0.30 mm. According to the particle size classification, one particle size sample is taken at a time, and 5 groups of 50 g (±0.5 g) prepared samples are weighed with the high-precision platform scale, numbered 1, 2, 3, 4, and 5. The weighed samples are evenly spread on the cork plate with the plastic cylinder mold according to the corresponding number, as shown in Figure 14.

Figure 14. Preparation of test samples.

After the samples are prepared, the samples are irradiated in the microwave oven for 4 s, 6 s, 8 s, 10 s, 12 s, 14 s, 16 S, 18 s, and 20 s, and the infrared thermal imager is used to obtain the temperatures before and after microwave exposure of the sample.

4.2. Test Procedure

(1) The infrared thermal imager is turned on for debugging, and the basic parameters of the instrument are set according to the test environment. During the test, the initial temperature of the environment is approximately 23 °C.

(2) The ambient temperature at the beginning of the test, the cavity temperature of the microwave oven and the initial temperature of the sample are obtained and recorded by the infrared thermal imager.

(3) In accordance with the cork plate number, samples are taken in sequence for testing. First, the temperature of the test sample before microwave irradiation is obtained by the infrared thermal imager. Then, the cork plate with a flat sample is placed on the glass box, as shown in Figure 15. After the sample is placed, the door of the microwave oven is closed.

Figure 15. Test samples before microwave irradiation.

(4) The irradiation time is set according to the required irradiation time, and the microwave oven irradiates the test sample according to the set time.

(5) When the microwave irradiation time is reached, the door of the microwave oven is opened, the test sample is carefully and quickly removed, and the infrared thermal imager (recognition accuracy of 0.1 °C) is immediately used to obtain the temperature spectrum of the sample after microwave irradiation, to ensure that the measurement area of each sample is consistent, as shown in Figure 16. Each temperature spectrum is encoded in four digits. The first letter represents the type and size of the sample, the second digit indicates the microwave irradiation time, the third digit represents the group number, and the fourth digit indicates before or after microwave irradiation, where 0 indicates before and 1 indicates after microwave irradiation. For example, C1-10-1-0 indicates S1 size coal sample-irradiation time 10 s-sample with group number 1-spectrum before microwave irradiation. The temperature spectra of C1-10 and G1-10 obtained in the test before and after microwave irradiation are shown in Figures 17 and 18.

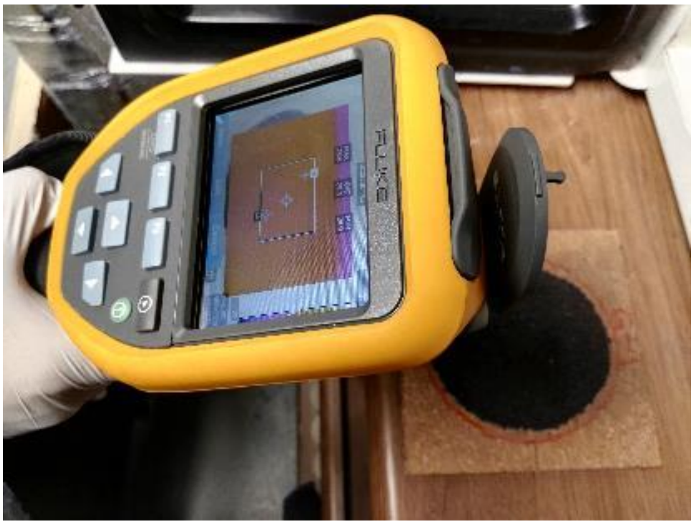
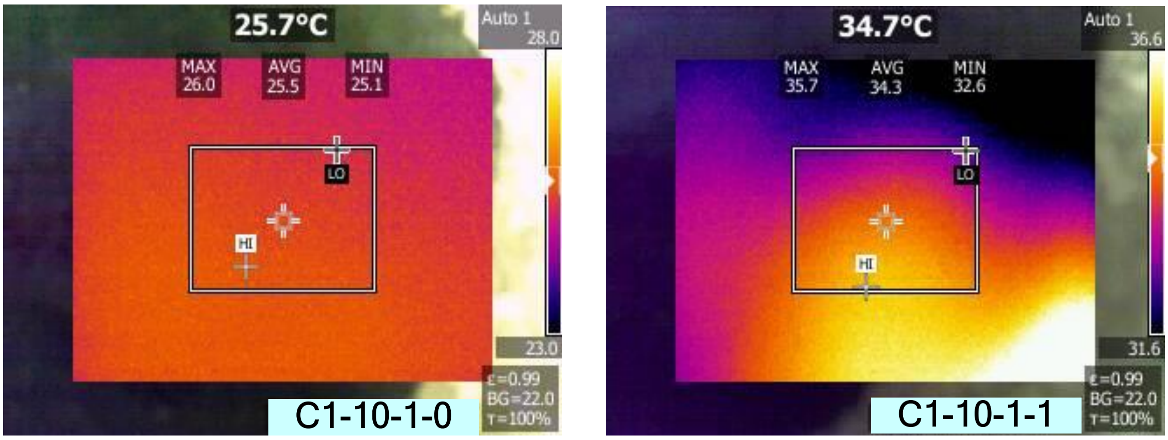
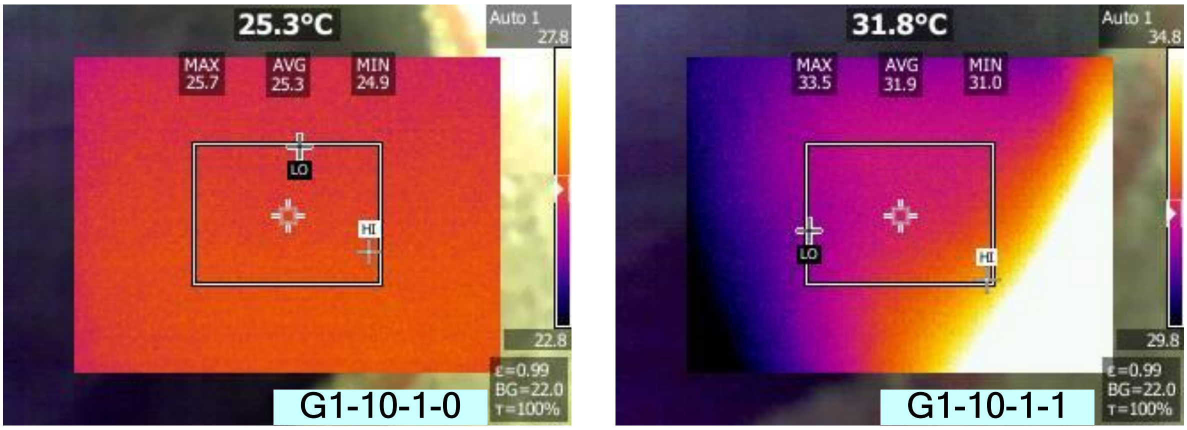


Figure 16. Infrared thermal imager to measure the temperature before and after microwave irradiation.



(**a**) (**b**)

Figure 17. Spectrogram of coal samples with size of S1 before and after microwave irradiation of 10 s. (**a**) Before microwave irradiation; (**b**) After microwave irradiation.



(**a**) (**b**)

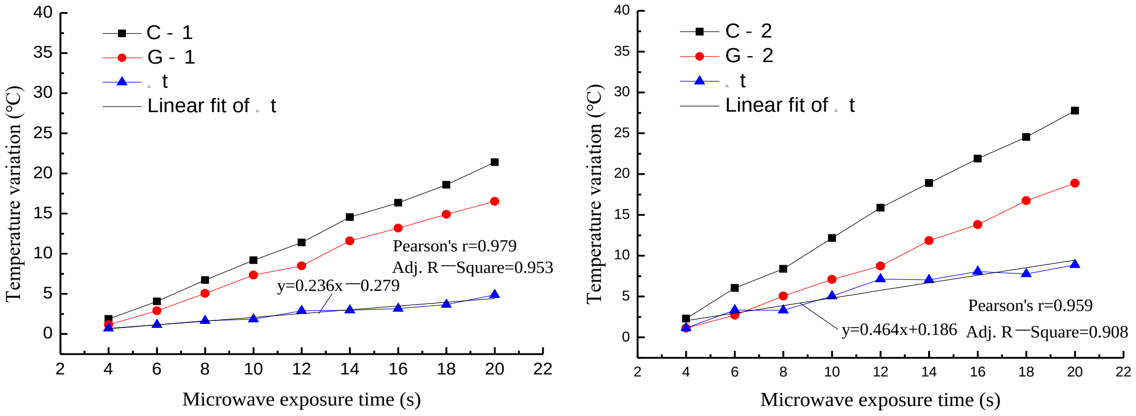
Figure 18. Spectrogram of gangue samples with size of S1 before and after microwave irradiation of 10 s. (**a**) Before microwave irradiation; (**b**) After microwave irradiation.

(6) After the test of a group of samples, the microwave oven is cooled to the initial temperature, and the cork plate and glass box are removed to cool to room temperature. The samples are returned to the sample table and naturally cooled to room temperature.

(7) When the temperature in the chamber of the microwave oven drops to the initial temperature, and the temperatures of the cork plate, glass box and sample drop to room temperature, the next group of sample tests is started, and the above test steps are repeated.

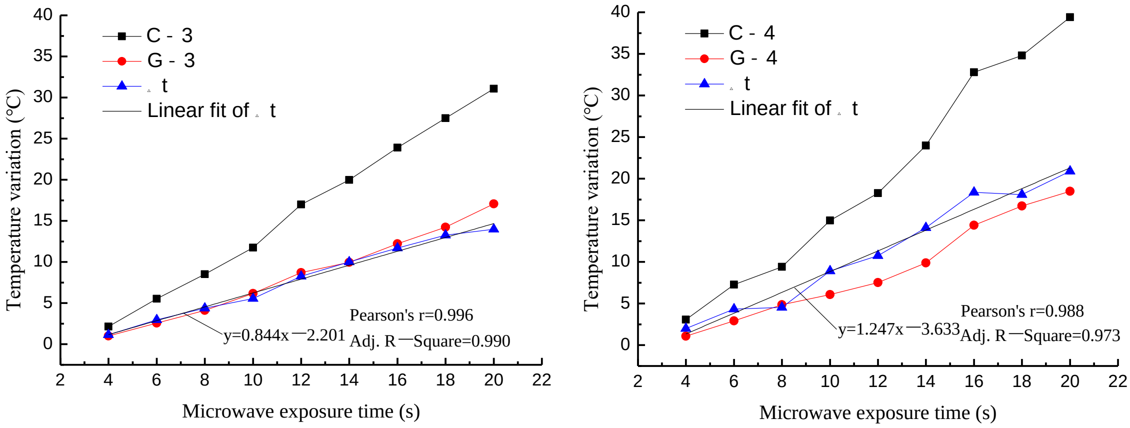
4.3. Test Data Analysis

All the test data are analyzed for gross errors, and after removing the gross error data, the normal temperature difference data of each group of coal and gangue samples before and after microwave irradiation are averaged. According to the temperature change values of coal and gangue samples under different microwave irradiation time conditions, the test results under the same coal and gangue particle size conditions are fitted with the relationship between the temperature change and microwave irradiation time using Origin 8.0 software, created by MicroCal company, from Northampton, MA USA. The combined curves are shown in Figures 19 and 20.



(**a**) S1 (**b**) S2

Figure 19. Results of coal and gangue microwave irradiation test under size S1 and S2.



(**a**) S3 (**b**) S4

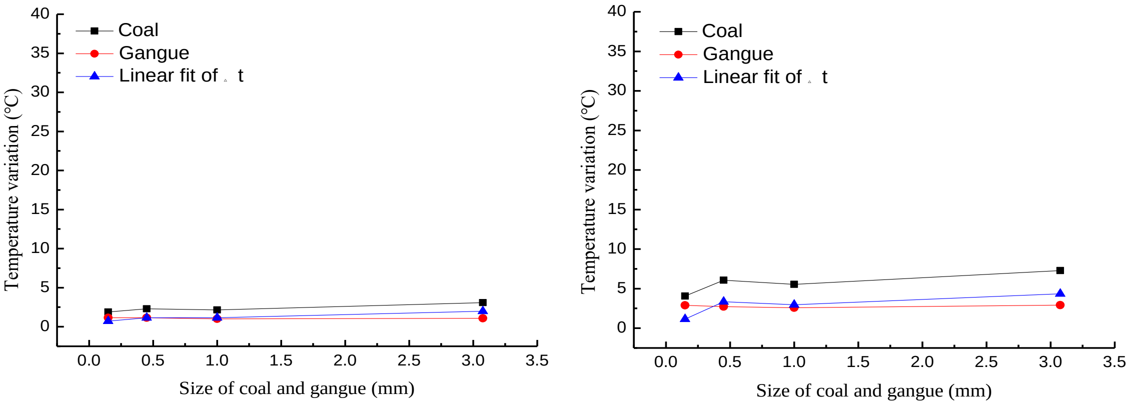
Figure 20. Results of coal and gangue microwave irradiation test under size S3 and S4.

Based on the above data analysis, it can be concluded that under the same coal and gangue particle size and microwave irradiation time conditions, in the order of particle size from small to large, the temperature increase of the sample coal particles after microwave irradiation is 1.3 times, 1.7 times, 2.0 times and 2.3 times that of gangue. This shows that the larger the particle size is, the greater the temperature ratio between coal and gangue under the same microwave irradiation, and the greater the absolute temperature difference.

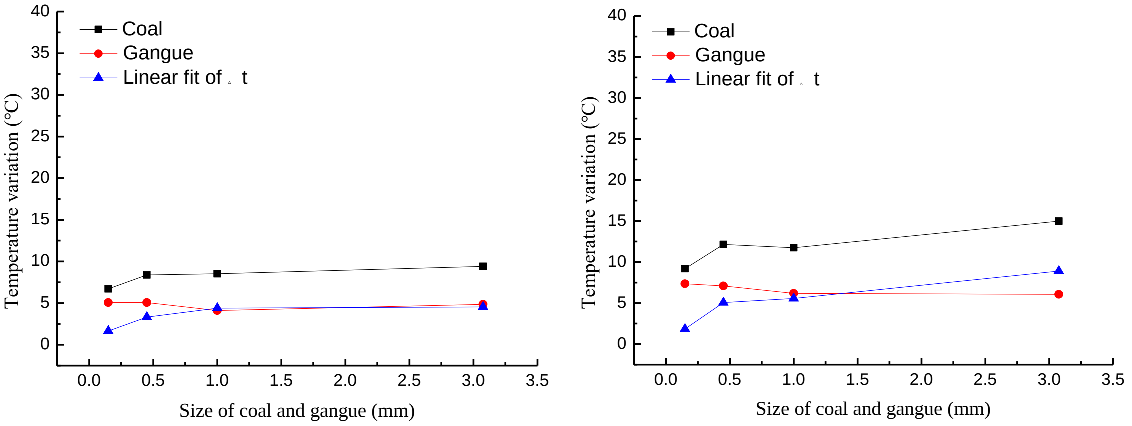
The temperature changes of coal and gangue after microwave irradiation are different, as shown in Figure 21. Under the same microwave irradiation time, the temperature change of coal sample after microwave irradiation increases with increasing particle size. The imaginary parts of the dielectric constant of coal samples with different particle sizes show that the smaller the coal sample size is, the larger the imaginary part of the dielectric constant, and the greater the ability to convert microwave into internal energy. Although the small particle size coal sample converts more microwave energy, the smaller the particle size of the coal sample is, the larger its contact area with the outside area, and the higher the thermal diffusion loss. When the thermal diffusion loss is greater than the microwave energy converted, the above-mentioned experimental results appear, that is, the temperature change of coal sample after microwave irradiation increases with increasing particle size.

With increasing microwave irradiation time, the heating rate of coal samples increases, because the specific heat capacity of coal samples at higher temperatures is smaller than that at lower temperatures. Therefore, under the same energy absorption conditions, the heating rate of coal samples under high-temperature conditions is higher than that under low-temperature conditions. Under different microwave irradiation time conditions, the heating rate of coal samples increases with increasing irradiation time, and the amount of temperature change increases with increasing particle size.

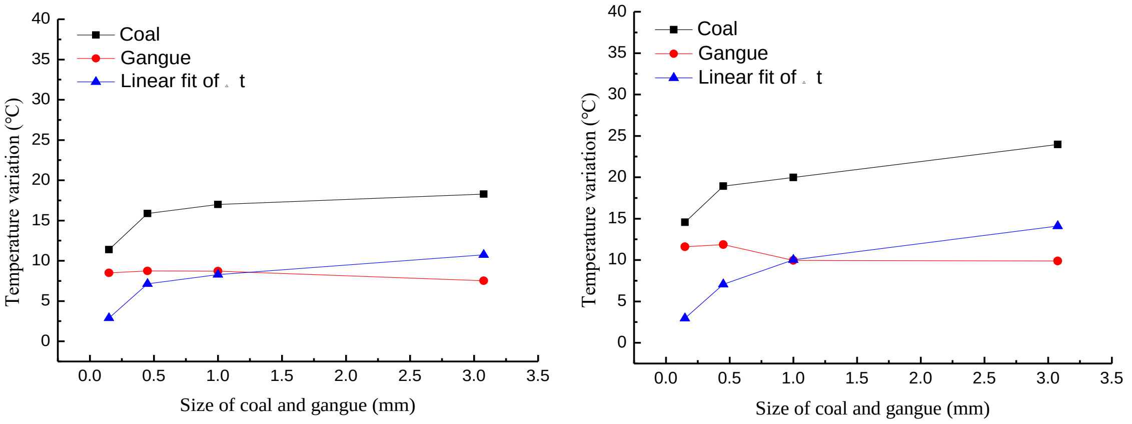
For the same microwave irradiation time, the temperature change of gangue samples after microwave irradiation has no change with increasing particle size, that is, the temperature change of gangue samples after microwave irradiation has no obvious difference with increasing particle size, which occurs because the imaginary part of the dielectric constant of gangue samples has no obvious difference with the change in the particle size. Due to the small changes in the specific heat capacity of gangue at different temperatures, the heating rate of gangue samples is relatively constant under different microwave irradiation times, and the temperature has no significant difference with increasing particle size.



(**a**) 4 s (**b**) 6 s

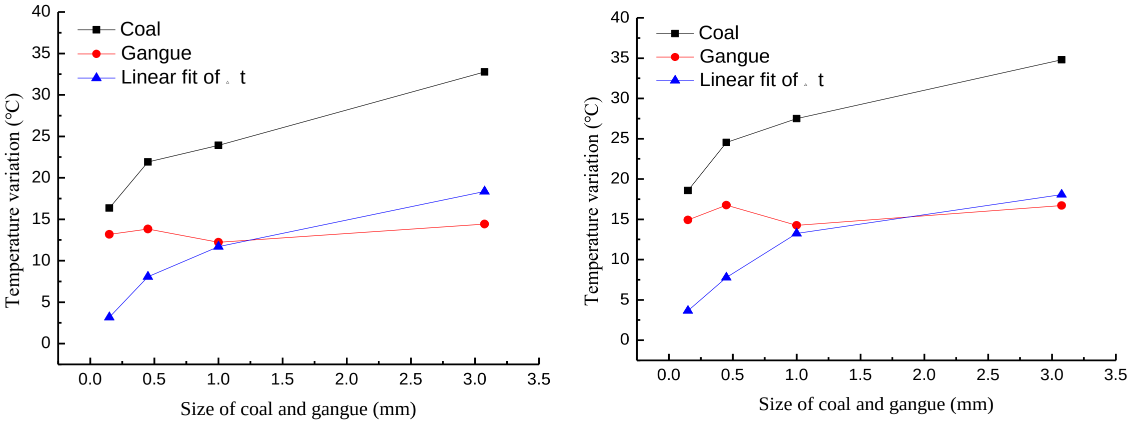


(**c**) 8 s (**d**) 10 s

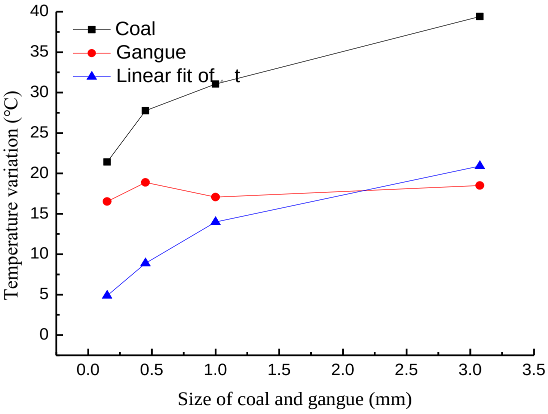


(**e**) 12 s (**f**) 14 s

Figure 21. *Cont.*



(**g**) 16 s (**h**) 18 s



(**i**) 20 s

Figure 21. Microwave thermosensitive test results of different coal and gangue sample size under different microwave irradiation time.

5. Conclusions

Under the same experimental conditions, temperature changes in coal and gangue after microwave irradiation are quite different. The difference between coal and gangue can be accurately estimated using an infrared thermal imager, which supports the feasibility of the active coal-gangue identification method based on microwave irradiation and infrared thermal imaging. Several interesting conclusions can be drawn from this study as follows.

(1) The main component of coal is organic matter mainly composed of carbon, accounting for 86.4%; The main components of gangue are kaolinite and quartz, containing some organic matter, and the main element component is oxygen, accounting for 38.2%, followed by carbon, accounting for 32.8%. The weight percentage of carbon in coal is 2.6 times that in gangue, and the number of polar molecules in coal is greater than that in gangue. Under the same microwave irradiation conditions, the ability of coal to absorb microwaves is 1.3 times that of gangue.

(2) Under the same microwave irradiation conditions, the average temperature rise of coal is approximately 1.5 times that of gangue.

(3) For the same microwave irradiation time, the temperature change of coal samples after microwave irradiation increases with increasing particle size, while the temperature change of gangue samples after microwave irradiation has no obvious difference with increasing particle size.

(4) Under different microwave irradiation times, the heating rate of coal samples increases with increasing irradiation time, and the temperature variation increases with

increasing particle size; the heating rate of gangue samples is relatively constant, and the amount of temperature change has no obvious difference with increasing particle size.

It should be noted that all experiments were conducted under the same moisture content. In addition, the influence of dust, which is common in LTCC operations, is not considered. Research on the influence of moisture content on thermal sensitivity of coal and gangue and the effect of dust on infrared thermal imaging is currently underway.

The research in this paper is far from being directly applied in the field, but it serves to demonstration the applicability of microwave irradiation method as a tool for coal-gangue identification

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