Electromagnetic signal characteristics and energy response pattern of briquette hammer fracturing

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Abstract
Briquette hammer fracturing experiments were conducted with different impact energies and molding pressures to investigate the characteristics of the electromagnetic signals. The response pattern of the electromagnetic radiation energy as a function of the impact energy and the coal firmness during impact fracturing of a coal mass were analyzed. The characteristics of the electromagnetic radiation signals during the uniaxial compression fracture of a coal mass were also used to analyze their source during fracture. The results show that the generation of electromagnetic radiation during coal mass fracturing can be divided into three stages: compaction, crack propagation and sliding friction. Electromagnetic energy is mainly radiated during the sliding friction stage. The electromagnetic radiation during briquette hammer fracturing is characterized by a frequency below 2000 Hz, an amplitude in the range from 0.05 to 0.6 mV, and a total energy on the order of $\sim 10^{-14}$–$10^{-10}$ J. For coal masses with the same firmness, as the impact energy increases, the total energy of the electromagnetic radiation increases. For the same impact energy, as the firmness of the coal mass increases, the total energy of the electromagnetic radiation first increases and then decreases.

Keywords: hammer fracturing, electromagnetic radiation, signal characteristics, energy, response pattern

1. Introduction

Coal and gas outburst and the shock bump are serious coal mine disasters. The processes of the preparation stage of coal and gas outburst and shock bump are accompanied by the redistribution of stress and the destruction of coal and rock. Monitoring the electromagnetic radiation signal in the process of coal and rock failure is a common non-contact disaster prediction method. By studying the characteristics of electromagnetic radiation signals in the process of impact damage, the electromagnetic radiation signal in the process of coal rock damage can be identified more accurately, which helps to improve the accuracy of early warnings.

Many studies have shown that the fracturing of a coal mass is accompanied by the generation of electromagnetic signals. Electromagnetic radiation technology has been applied in areas such as predicting coal and gas outbursts (Sa et al. 2004; Qiu et al. 2018), localizing seismic sources (Li et al. 2014), assessing the coal bump risk (He et al. 2019), evaluating the effect of coal seam hydraulic flushing (Shen et al. 2018) and detecting goafs. However, the mechanism of electromagnetic signal generation during coal mass fracturing has not been sufficiently studied. Nitsan (1977) analyzed the electromagnetic radiation emitted during uniaxial compression and proposed that the piezoelectric effect is the main cause of electromagnetic radiation from coal and rock. Leeman et al. (2014) observed an electromagnetic radiation anomaly during a stick-slip friction experiment and argued that the triboelectric effect is the main
reason for an electromagnetic radiation signal generated prior to fracture. Song et al. (2018) studied the characteristics of electromagnetic radiation signals and their influencing factors. Some researchers have studied the characteristics of electromagnetic radiation signals during the coal damage process and proposed a radiation mechanism (Frid et al. 1992; Frid & Vozoff 2005; Li et al. 2015, 2016, 2017; Qiu et al. 2018). Song et al. (2012) studied the characteristics of electromagnetic radiation signals under cyclic loading. Kong et al. (2017) investigated the time-varying characteristics of electromagnetic radiation during the coal-heating process. Li et al. (2018) tested the electromagnetic radiation characteristics of concrete specimens after exposure to elevated temperatures. Lou et al. (2019) studied the correlations between acoustic and electromagnetic emissions and stress drop induced by burst-prone coal and rock fracture. He et al. (2012) researched the electromagnetic radiation in gas-containing coal and rock fracture.

The complexity of geological conditions and production states makes it impossible to accurately predict disasters using just a single electromagnetic signal indicator. The reasonable selection of indicators for evaluating signal anomalies to predict electromagnetic radiation is also an important research task. Based on the relationship between electromagnetic radiation signals and stress, Wang et al. (2011) proposed an electromagnetic radiation method for evaluating mine pressure. Liu et al. (2015) studied electromagnetic radiation early warning technologies for dynamic coal and rock disasters. Sa et al. (2004) conducted in-depth research on the use of the number of pulses and the intensity of electromagnetic radiation as indicators for judging the risk of coal and gas outbursts, and identified the critical values of these parameters and methods for identifying abnormal electromagnetic radiation signals. Li et al. (2014) proposed the use of energy as an indicator for locating local seismic sources in coal rock. In terms of the mode of fracture of a loaded coal mass, Yao et al. (2012, 2016) studied the dynamic multifractal characteristics of electromagnetic radiation during the uniaxial compression fracture of a coal mass and analyzed the pattern of electromagnetic radiation signals in this process based on energy theory. To predict electromagnetic radiation more accurately, it is necessary to further study the mechanism by which electromagnetic radiation is generated.

In this study, briquettes molded under different pressures were used to characterize coal masses with different levels of firmness, and different hammer heights represented different impact energies. The hammer fracturing experiment was used to study the response pattern of the electromagnetic radiation signal energy as a function of the impact energy, and the coal firmness during impact fracture and the causes for the corresponding pattern were mechanistically analyzed.

2. Analysis of electromagnetic signal sources during coal body fracture

The hammer fracturing of a coal mass and the electromagnetic radiation signals generated during fracture are extremely brief (usually less than 0.1 s, as shown in figure 8), which makes it difficult to analyze their source. The electromagnetic radiation signal is mainly caused by coal body failure. Both the static load and dynamic load can cause coal body failure. Therefore, electromagnetic radiation signals can be generated in both the process of the static load and dynamic load failure. Even the uniaxial compression and hammer fracture have different failure characteristics, but their electromagnetic signal sources are similar. This paper proposes using uniaxial compression, which has a relatively long duration, to investigate the source of the electromagnetic radiation signals that are present when a coal mass fractures. Additionally, a test experiment on the electromagnetic radiation due to uniaxial compression of a coal mass is designed. Figure 1 shows part of the devices of the coal uniaxial compression experiment. The loading device is a servo press that provides the loading force and records it during the uniaxial compression process. The receiving antenna can receive the electromagnetic radiation signals produced by coal failure. The receiving antenna used in the system is a magnetic rod antenna. When the environmental magnetic field changes, the induced electromotive force will be generated. The electromagnetic radiation signal is measured by measuring the magnitude of the induced electromotive force. The height and basal diameter of the coal sample are 100 and 50 mm, respectively.

Figure 2a shows the original electromagnetic signals of the coal sample during uniaxial compression. It can be seen that the signal-to-noise ratio of the original signal is very low, and the denoising process is necessary. Fourier transform was performed on the original signal. Figure 2b shows
Figure 2. The electromagnetic signals during uniaxial compression.

Figure 3. Experimental results of uniaxial compression electromagnetic radiation test.

2.1. Compaction stage

In the initial stage of uniaxial loading, the uniaxial stress increased slowly and no cracks were found in the coal sample. Because the briquette samples contained many original pore cracks, the original pores began to close under the uniaxial stress and there was weak friction between mineral particles, which resulted in trace heterogeneous charges. Because the amount of charge generated was small and coal is a poor conductor, only weak electromagnetic radiation signals were detected, as shown in figure 3.

2.2. Crack expansion stage

As loading continued, the uniaxial stress continued to increase and cracks appeared in the coal sample accompanied by sounds. During crack formation, the chemical bonds between the atoms on the leading edge break under the concentrated stress at the crack tip. Free charges with opposite signs built up on both sides of the wall, resulting in electromagnetic radiation signals. The small number of free charges generated by the propagation of the microcracks and the large number of cracks led to weak, dense electromagnetic signals, as shown in figure 3. The distinction between the compaction stage and the crack expansion stage is mainly based on the electromagnetic radiation signals. The electromagnetic radiation signal corresponding to the red ellipse in figure 4 shows...
that the electromagnetic radiation signal in the crack expansion stage was more intensive than that in the compaction stage, even though their amplitudes are small.

2.3. Slip friction stage

As the cracks continued to propagate, the original cracks coalesced with the new cracks to generate main cracks. This process caused the coal mass to undergo severe fracturing. At the same time, the uniaxial stress decreased rapidly and the pressure in the sample was relieved. Severe sliding friction occurred on both sides of the crack wall. The friction and relative motion of the crack surface generated many free electrons, and their movements resulted in significant transient electromagnetic signals being observed at this stage, as shown in figure 3. Moreover, the energy of the electromagnetic radiation signals generated at this stage accounted for more than three-quarters of the total energy of the signals, as shown in figure 4. There are different opinions on the mechanism of electromagnetic radiation of coal rock fractures, such as the piezoelectric effect, friction effect, charge separation, thermionic emission, field emission, ionization of colliding pore gas and flow potential. The charge motion modes include transient electric dipole, crack propagation, crack wall oscillation circuit, relaxation and bremsstrahlung, among others. According to these experimental results, the slip friction stage accounted for more than three-quarters of the total energy of the signals. Based on the theoretical analysis, this stage mainly includes the following processes: the friction between minerals in coal samples, the charge separation in crack growth and the free electron movement in the process of local crack. Therefore, in our opinion, the main sources of electromagnetic radiation in the process of coal body destruction by hammering mainly include: the friction between minerals in coal samples, the charge separation in crack growth and the free electron movement in the process of local crack.

3. Hammer fracturing experiment

3.1. Experimental device and system

A drop hammer impact system for measuring electromagnetic radiation was constructed based on the drop weight method shown in figure 5. The system consists of two parts. The first part consists of the drop hammer loading device, the main components of which are a heavy hammer, a control track, transmission rods, the coal samples to be tested and a base. The other part is the electromagnetic signal acquisition system, the main components of which are a magnetic rod antenna, a ZDKT-1 data acquisition system and a computer. The loading and data acquisition systems are shown in figure 6.

The drop hammer loading device controls the hammer speed by adjusting the height of the heavy hammer. The heavy hammer and the transmission rod have a running rail made of stainless-steel pipes to control their running track and to ensure frontal impact on the coal sample. In the experiment, the heavy hammer was lifted to a preset height and then allowed to fall freely. The hammer struck the transmission rod, which transmitted the impact load to the sample. To prevent the metal components from interfering with the electromagnetic signals during loading, the heavy hammer, the transmission rod and the base were all made of nylon. The hammer had a weight of 9 kg and a diameter of 75 mm, the diameter of the transmission rod was 75 mm, the diameter of the base 140 mm and the inner diameter of the track was 80 mm.

The electromagnetic signals generated by the fracturing of the coal samples were received by the receiving antenna. The receiving antenna was based on Ferrari’s law of electromagnetic induction and was mainly composed of coils. When the magnetic flux in the receiving antenna changed, an induced electromotive force was produced in the coils. The ZDKT-1 data collection system can convert the voltage signals into digital signals, which can be saved and shown in the collection software installed on the computer. To maximize the reception of magnetic signals, the receiving antenna must directly face the coal sample and be kept at the same level as the coal sample during the experimental process. The optimum distance between the antenna and the coal sample is 4 cm.
The maximum sampling frequency of the ZDKT-1 data collection system is 51 kHz and a frequency of 29.6 kHz was used in the experiments. Before the hammer falls, the receiving antenna must be in the right position and the data collection system and the collection software must be turned on. During the experiment, all electrical equipment, except for the equipment required to conduct the experiment, such as the lights, had to be turned off to reduce the influence of environmental noise. The entire experiment had to be finished in one day.

### 3.2. Briquette preparation

The coal sample was selected from lump coal from the face 21 200 of the Dongpang Mine belonging to the Jizhong Energy Group. To determine the characteristics of the electromagnetic signals generated during the hammer fracturing of coal masses with different levels of firmness, pulverized coal with three different particle sizes was pre-sieved, and then the pulverized coal and coal tar (mass ratio 260:13) were evenly mixed. Finally, a servo press was used to process the mixture into standard coal samples of $\Phi 50 \times 100$ mm under different molding pressures for 12 hours. A total of 20 groups were prepared and numbered DX-1 through DX-20. It should be noted that 21 coal samples are prepared in this experiment, as shown in figure 7, but the first coal sample was used to test the experimental equipment at the beginning and the data of this coal sample was not analyzed in our research.

### 3.3. Experimental scheme

The experimental variables were set as shown in Table 1.
Table 1. Experimental scheme for coal mass hammer fracturing to determine the energy characteristics of the electromagnetic radiation signals.

| Variable                  | Number | Molding particle size (mm) | Molding pressure (kN) | Impact energy (J) |
|---------------------------|--------|----------------------------|-----------------------|-------------------|
| Impact energy             | DX-19  | 0–0.25                     | 160                   | 194.48            |
|                           | DX-20  | 181.25                     | 168.02                |                   |
|                           | DX-1   | 168.02                     | 155.23                |                   |
|                           | DX-17  | 155.23                     | 142.44                |                   |
| Molding pressure          | DX-2   | 0–0.25                     | 42.8                  | 168.02            |
|                           | DX-3   | 100.9                      | 168.02                |                   |
|                           | DX-4   | 220                        | 168.02                |                   |
|                           | DX-5   | 280                        | 168.02                |                   |
|                           | DX-6   | 340                        | 168.02                |                   |
| Molding pressure          | DX-8   | 0.25–0.5                   | 100.9                 | 168.02            |
|                           | DX-9   | 160.3                      | 168.02                |                   |
|                           | DX-7   | 220.8                      | 168.02                |                   |
|                           | DX-10  | 280                        | 168.02                |                   |
|                           | DX-11  | 340                        | 168.02                |                   |
| Different molding pressure| DX-12  | 0.5–1.0                    | 100                   | 168.02            |
|                           | DX-13  | 160                        | 168.02                |                   |
|                           | DX-14  | 220                        | 168.02                |                   |
|                           | DX-15  | 280                        | 168.02                |                   |
|                           | DX-16  | 340                        | 168.02                |                   |

4. Denoising and analysis of the characteristics of the electromagnetic radiation signals

The original electromagnetic radiation signals measured in two experiments are shown in figure 8. The electromagnetic radiation signals in the process of impact failure of coal and rock mass are typically unsteady signals and the noise mainly comes from the relatively stable system noise. Based on the characteristics of these original signals, this paper proposes the use of the base signal removal (BSR) method and empirical mode decomposition (EMD) to denoise the original signals. The BSR method involves selecting an unmutated portion that agrees well with the base signal after the transient interval signal has been determined and obtaining a BSR-processed target signal by subtracting the base signal from the original target signal. Then, EMD is used to decompose the BSR-processed signal into intrinsic mode functions (IMFs) that satisfy the corresponding conditions. The process of obtaining the IMFs by EMD is given by

\[ S(t) = \sum_{j=1}^{n} IMF_j(t) + r(n), \]

where \( S(t) \) is the original signal; \( IMF_j(t) \) is the \( j \)th IMF; \( n \) is the scale of the decomposition and \( r(n) \) is the residual of the decomposition, which represents the trend of the signal.

In the obtained IMFs, the components that change suddenly are selected and added to obtain the denoised signal, as shown in figure 9. Analyzing the amplitudes of the electromagnetic signals of all the experimental groups shows that the amplitudes of the electromagnetic radiation signals emitted during hammer fracturing range from 0.05 to 0.6 mV (figure 10).

The electromagnetic radiation energy emitted during hammer fracturing, according to the method for calculating the instantaneous radiation energy of the electromagnetic radiation signals, is expressed by

\[ E = \sum_{i=1}^{n} \frac{V_i^2}{R} \cdot \Delta t = \sum_{i=1}^{n} \frac{V_i^2}{R} / f_s \]

where \( \Delta t \) is the time interval between two sampling points; \( f_s \) is the sampling frequency; \( n \) is the number of sampling points and \( V_i \) is the voltage at the \( i \)th sampling point. \( R = 50 \Omega \) is the internal resistance of the magnetic rod antenna.

As shown in figure 11, the total electromagnetic radiation energy measured for each of the groups is on the order of \( 10^{-14} - 10^{-10} \) J, and mostly on the order of \( 10^{-13} - 10^{-11} \) J. This is consistent with the findings of Gershenzon and Bambakidis (2001). The outlier in figure 11 may be a result of the briquette preparation process.

Theoretically speaking, in the process of static load failure, the continuous loading on the material will cause the accumulation of strain energy inside; once the accumulated energy exceeds the ultimate value limited by the mechanical properties of materials, internal fracture generation and external damage will occur. In the process of fracture and damage, electromagnetic radiation signal will be produced. Therefore, the electromagnetic radiation signal will occur intermittently in the process of static load and last the whole process, and there is a large amplitude electromagnetic radiation signal when the specimen is completely broken. Due
to the short time of dynamic damage, only a violent electromagnetic radiation signal appears at the end of the failure. The above analysis can be validated by comparing the coal failure of electromagnetic radiation signals during the uniaxial compression process and the impact process in this research.

Through comparing the electromagnetic radiation signal during SHPB coal failure (Li et al. 2016) with the experimental results in this paper, it can be seen that the waveform of the electromagnetic radiation signal in the two processes is similar, and the relationship between radiation energy and impact failure energy is also similar.

5. Response pattern of the electromagnetic signal energy

5.1. Response pattern of the electromagnetic signal energy as a function of the impact energy

As shown in figure 12, for coal masses made with the same molding pressure and particle size, as the impact energy increases, the electromagnetic radiation energy generated during fracture increases. According to the analysis, because uniaxial compression and hammer fracturing have similar force action modes and fracture modes, it can be assumed that the source of the electromagnetic radiation signals is approximately the same during hammer fracturing and uniaxial compression. As the impact energy increases, the stress acting on the coal mass and the frictional strength of the compaction stage increase. More new cracks are generated in the crack propagation stage, and a higher speed of slip friction, a higher strength of action, and a larger area of action are produced in the slip friction stage. When these results are combined with the previous analysis of the electromagnetic signal source, it can be concluded that as the impact energy increases, the electromagnetic radiation energy of fracturing the coal mass increases in each stage, leading to an increase in the total energy of the electromagnetic radiation signals. Therefore, in field applications, the amount of electromagnetic radiation energy can be used to approximately reflect the magnitude of the impact energy received by the coal mass. The response pattern of the electromagnetic signal energy as a function of the impact velocity is shown in figure 13. It can be seen that the response pattern of the electromagnetic signal energy as a function of the impact velocity is similar to that of the impact energy.
5.2. Response of the electromagnetic signal energy to the molding pressure

As shown in figure 14a, for a given hammer height, as the molding pressure on the coal briquette samples with a particle size of 0 to 0.25 mm increases (within the experimental pressure range), the electromagnetic radiation energy first increases and then decreases. In comparison, for the coal briquette samples with particles larger than 0.25 mm, the electromagnetic radiation energy increases with the molding pressure within the experimental pressure range, as shown in figures 14b and 14c.

According to the analysis, as the molding pressure increases, the coal mass becomes denser and has fewer original cracks. For a given impact energy, the number of cracks reaching the condition for propagation is correspondingly lower. When combined with the earlier analysis of the electromagnetic signal source, this result shows that less electromagnetic signal energy is generated in the coal sample during compaction and crack propagation. Because a coal mass made with higher molding pressures has a more compact coal structure, and assuming that the impact energy can still cause many cracks in the coal sample in the sliding friction stage of coal mass fracture, the actual contact area of the crack friction surface is larger, which means that more electromagnetic radiation energy is produced in this stage. For a given impact energy, as the firmness of the coal mass continues to increase, no cracks or only very few cracks can be produced in the coal mass. Under these circumstances, the frictional sliding surfaces of the cracks in the coal mass are substantially smaller, and therefore, less electromagnetic radiation energy is generated in this stage. It can be seen from the source of the electromagnetic signals mentioned earlier that the energy of the electromagnetic radiation signals can account for 3/4 of the total energy of the signals in this stage. Therefore, the results obtained in figure 14a can be reasonably explained. A downward trend is not observed in figures 14b or 14c. The analysis indicates that this is because the large molding particle size lowers the firmness of the coal mass. With the experimental impact energy, many cracks can still form in the two coal briquette sample groups. As the molding pressure
continues to increase, the electromagnetic radiation signals may show a downward trend, and this trend will be shown in subsequent studies. Therefore, when the electromagnetic radiation signal energy is used to predict coal and gas outbursts and rock bursts, the critical value should be determined using the specific properties of the coal mass. Among these properties, the firmness coefficient of the coal mass has an important influence.
6. Conclusions

(1) The friction between minerals in coal samples, the charge separation in crack growth and the free electron movement in the process of local crack development are the main sources of electromagnetic radiation in the process of coal hammer failure. These three parts of energy account for more than three-quarters of the total electromagnetic radiation energy during coal hammer failure.

(2) The electromagnetic radiation signals of the briquette during hammer fracturing have frequencies lower than 2000 Hz and are therefore low-frequency signals. The total energy in the electromagnetic radiation of the briquette during hammer fracturing is on the order of $10^{-14} - 10^{-10}$ J.

(3) With the increase of impact energy, the total energy of electromagnetic radiation of coal with the same hardness increases. Radiation energy can reflect the impact energy in the process of coal impact failure and it can be selected as an effective index for predicting the coal mine impact disasters.

(4) For the given impact energy, with the increase of coal hardness, the total energy of electromagnetic radiation increases first and then decreases. The selection of the prediction index threshold based on the electromagnetic radiation method is closely related to the physical and mechanical properties of the coal body.

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