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Fine coal desulfurization and modeling based on high-gradient magnetic separation by microwave energy

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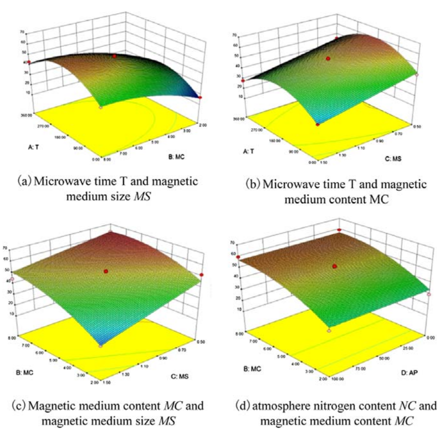
GRAPHICAL ABSTRACT



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ABSTRACT

Fine coal separation is one of the research focuses in the field of clean coal technology. A new type of fine coal dry separation technology was studied. Microwave energy was used to strengthen the magnetic properties of coal pyrite, leading to high- gradient magnetic separation. A high-intensity magnetic separator was used for the separation of fine coal, and an effective way to achieve the clean utilization of pulverized coal before its combustion was investigated. The R^2 and corrected R^2 values of the two-order model according to the sulfur content of clean coal were small. This shows that the recommended model has a higher fitting degree of response surface. Microwave pretreatment time *T* has a higher sensitivity to the sulfur content of clean coal than *MC* in a given range. The response surface has an optimal value, i.e., the highest desulfurization rate. With the increase in magnetic particle size, the desulfurization rate increased continuously. The evaluation index of the clean coal sulfur content of fine coal microwave-enhanced magnetic desulfurization test was optimized by a better two-order fitting model. The constraint conditions of the main influencing factors and the optimization indexes after the response were obtained. The sulfur content of clean coal was in the range of [1.98, 3.35].

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Table 1
The proximate, ultimate and sulfur analysis of coal samples.

Coal number	M_{ad}%	A_d%	V_{daf}%	$F_{C.d}$%
Lu An	1.72	29.30	19.67	56.79
O_{daf}%	C_{daf}%	H_{daf}%	N_{daf}%	$S_{t.d}$%
4.92	84.34	4.38	1.18	3.66
Coal type	$S_{t.d}$%	$S_{p.d}$%	$S_{s.d}$%	$S_{o.d}$%
Meagre coal	3.66	2.15	0.37	1.14

1. Introduction

Coal is the second largest primary energy resource in the world; it is the main energy resource in the energy structure of China and will not change in a fairly long period of time [1]. Coal separation technologies, mainly the wet coal separation technologies, are crucial for the utilization of clean coal. However, as coal mining is shifted to cold and dry areas, such as > 2/3rd of the coal reserves are distributed in the western arid area in China, efficient dry coal separation technologies should be developed [2,3]. Fine coal separation is one of the research focuses in the field of clean coal technology, and a lot of research has been carried out. Dry fine coal separation technologies are mainly compound dry separation [4,5], air jig sorting [6–8], autogenous medium vibration fluidized bed [9,10], magnetically stabilized fluidized bed [11], air dense medium fluidized bed [12–16], pulsating heavy medium fluidized bed [17], triboelectrostatic beneficiation [18,19], microwave magnetic separation [20–24], and high-gradient magnetic separation [25–27].

At present, the dry coal gravity separation method is mainly aimed at +0.5 mm fine coal, the triboelectric beneficiation method is mainly aimed at −0.045 mm fine particle coal. However, the high-gradient magnetic separation desulfurization technology is still in the laboratory research stage; there is still a lack of an efficient dry separation method for −0.5 mm +0.045 mm fine coal powder. Microwave radiation is an effective heating method. The magnetic properties of pyrite in coal are enhanced by using this method, benefiting magnetic separation [26,27]. For a low-rank coal, microwave heating decreases the moisture content of coal and increases its calorific value and fixed carbon content, thus improving the quality of lignite energy [28,29]. This is good for the subsequent selection of friction electrical work [30]. Similar to microscopic electrical polarization, microwave heating involves displacement of electrons, ions, dipoles, and space-charges, controlling the heterogeneous system of interfacial polarization [31–33].

In this study, a new type of fine coal dry separation technology was investigated. Microwave energy was used to strengthen the magnetic properties of coal pyrite, leading to high- gradient magnetic separation. A high-intensity magnetic separator was used for the separation of fine coal, and an effective way to achieve the clean utilization of pulverized coal before its combustion was investigated.

2. Experimental design and analysis of coal

In this study, mainly the pretreatment conditions of high sulfur coal and medium-high sulfur coal in the fine coal were considered, and S_{rej} was used as the index to evaluate the separation effect of separation test. The most commonly used desulfurization evaluation index S_{rej} can be expressed as follows:

$$S_{rej} = \frac{M_r - M_c \times Y}{M_r} \times 100\%$$

S_{rej} was used as the index to evaluate the separation effect of separation test.

3. Microwave-enhanced magnetic separation desulfurization test

3.1. Experimental analysis of Box–Behnken response surface method

Microwave-enhanced magnetic separation desulfurization test of fine coal was conducted for the analysis of multiple factors using the Box–Behnken response surface method. The interaction effects were evaluated only by using statistical DOE techniques. [34–35]. A microwave instrument with a frequency of 2450 MHz was used in the experiment. The microwave power was 1000 W, and the particle size of the sample was −0.5 mm. A strong rare-earth magnetic roller type magnetic separator was used. For the LuAn coal, $S_{t.d}$ was 3.66%, and in the sulfur speciation analysis of the coal, $S_{p.d}$ was 2.15%, $S_{a.d}$ was 1.14%, and $S_{s.d}$ was 0.37% in Table 1. The design of Box–Behnken response surface method requires only three levels, −1, 0, +1, and can used to design the factor of 3–21.

A two-level factorial was designed with an incomplete block design and analysis of creating statistical characteristics with the ideal design, because only three levels are suitable for two-time models. Table 2 shows the factors and levels of the Box–Behnken response surface method for microwave-enhanced fine coal desulfurization by magnetic separation. The effects of four factors *T*, *MC*, *MS*, and *NC* in the microwave treatment atmosphere of multiple factors experiments were considered. *T*, *MC*, *MS*, and *NC* are the microwave pretreatment time, magnetic particle content, magnetic particle size, and *NC*, respectively. The fine S_j, S_{rej}, and γ_j were used as the three indexes to evaluate the separation effect of the separation test. Table 3 shows the experimental results of Box–Behnken response surface method for microwave-enhanced fine coal desulfurization by magnetic separation.

3.2. Response surface analysis test of coal sulfur - S_j

The sulfur index of clean coal was analyzed after the magnetic separation. First, the approximate response model of clean coal sulfur was tested for suitability. As shown in Tables 4 and 5, when Prob > F is far < 0.05, the fitting of curve for the approximation model is higher. It can be concluded that the three-order model is a mixed model and thus not recommended. The results show that the Prob > F of the two-order model is < 0.0001, far < 0.05, and can be regarded as a model recommended by the system. At the same time, in addition to the three-order model, the standard variance of the two-order model is the smallest, and the R^2 and the predicted values are the largest, indicating that the fitting degree of the model is good. The sum of squares (Press), degree of freedom (DOF), Mean Square, F value and Prob > F were the commonly used as statistics index. The sum of squares (Press) was used to analyze the dispersion of experiment data and the lower value depicted the lower dispersion. The degree of freedom (DOF) was used to the number of illustrate the independent square in the data. The Mean Square was also used to analyze the dispersion of experiment data in

Table 2
Factor level table of Box-Behnken *RSM* of microwave strengthen magnetic fine coal desulfurization.

Factors	Minimum	Maximum	Mark number		Average
Microwave time/s	0	360	−1.000 = 0	1.000 = 360	180
Magnetic medium content/%	2	8	−1.000 = 2.00	1.000 = 8.00	5
Magnetic medium size/mm	0.5	1.5	−1.000 = 0.50	1.000 = 1.50	1
Atmosphere nitrogen content	0	100	−1.000 = 0	1.000 = 100	50