Fuel Processing Technology 147 (2016) 2–11

Contents lists available at ScienceDirect

Fuel Processing Technology

journal homepage: www.elsevier.com/locate/fuproc

Effect of microwave irradiation on the grinding characteristics of Ximeng lignite

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ARTICLE INFO

Article history:
Received 12 June 2015
Received in revised form 28 September 2015
Accepted 28 September 2015
Available online 18 November 2015

Keywords:
Grindability
Lignite
Microwave irradiation

ABSTRACT

The grinding characteristics of untreated and microwave-treated Ximeng lignites (XLs) were investigated, and the effects of microwave irradiation time, particle size range, and initial moisture were studied. The mass fraction and particle size distribution of the fine ground product with <0.154 mm particle size range of untreated and microwave-treated XLs were obtained. According to the analysis results of proximate, scanning electron microscopy and nitrogen absorption, the dominant mechanisms that improved the grindability of XL with high moisture under microwave irradiation included the rapid removal of moisture within the XL and the destruction of the pore structure induced by the steam jet flow generated with moisture removal. Microwave irradiation could improve the grindability of XL with high moisture, thus increasing the breakage rate of microwave-treated XL and mass fraction of the fine ground product significantly. The particle size distributions of the fine ground products of untreated and microwave-treated XLs changed slightly. With increasing microwave irradiation time, initial moisture, and particle size range of XL, the increment in the grindability of microwave-treated XL increased. When XL was treated at low microwave power, the microwave irradiation time was extended properly to avoid the accumulation of moisture on the surface. Therefore, the grindability of microwave-treated XL improved significantly.

1. Introduction

A large amount of pulverized coal is consumed by coal-fired power plants for electric power generation. However, because the combustion of oversized coal powder in boilers has an unfavorable effect on the timely ignition and complete burnout of pulverized coal, power stations have strict requirements on the particle size of pulverized coal [1]. The milling system in a power plant consumes a significant amount of energy and has a direct connection with the operational economy of a power plant. Coal grindability is an important factor that affects the operational efficiency of a milling system. Hence, if the grindability of coal can be significantly improved, the energy consumption of a milling system can be greatly reduced and the operational economy of a power plant can be improved.

In general, several factors affect the hardness of coal: coal rank, moisture content, petrography, and distribution and type of mineral [2–4]. A higher moisture content of coal and lower coal rank lead to the greater the reduction of coal grindability [5]. Lignite is a type of low-rank coal that has the characteristics of high moisture content, low calorific value, and easily spontaneous combustion, which limit its application in industries. Abundant lignite resources can be found in China, and the proven lignite reserves in Inner Mongolia account for 77.55% of the total lignite reserves in China [6]. Hence, the study of the various properties of Ximeng lignite (XL) is a good guide for utilizing the lignite resources in China.

The fundamental differences between microwave- and conventional-heating mechanisms exist [7]. During microwave drying, the polar molecules of materials experience dielectric loss in the applied high-frequency alternating electric field, causing microwave energy loss in the form of heat and increasing the temperature of the material [8]. Microwave is a type of electromagnetic energy that can deeply penetrate a material and cause volumetric heating. However, not all materials can adsorb microwave energy and be heated rapidly. On the basis of the behavior of materials in the microwave field, materials may be classified into the following three groups: conductors, insulators, and absorbers [9]. Insulators are transparent to microwave. Therefore, microwave can penetrate through the insulators and will not be attenuated. Given that conductors reflect microwave, they are not able to absorb microwave. Materials that can absorb microwave are called absorbers or dielectrics. As mentioned above, absorbers can absorb microwave energy and convert microwave into heat by dipole polarization or ionic conduction.

Coal is an organic macromolecular solid material that contains different inorganic minerals and is structurally heterogeneous, amorphous, and porous. Given that the loss factor for organic macromolecular structures in coal is low, the coal matrix as a bulk material has poor microwave energy absorption capability [10]. However, other phases within the coal matrix, such as moisture and some mineral impurities (such as pyrite), have high loss factors. Therefore, moisture and pyrite are more effective in microwave heating and can be heated at a faster

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http://dx.doi.org/10.1016/j.fuproc.2015.09.030
0378-3820/

rate than the rest of the coal matrix [11,12]. The coal matrix selectively absorbs the microwave energy in the microwave field because of its anisotropy. The differential heating of each phase within the coal matrix causes thermal stress and induces fractures within the coal particles; these effects are good for improving the grindability of coal. Furthermore, the moisture within the coal matrix will evaporate after absorbing microwave energy and the steam pressure field is established within the coal particles; therefore, the moisture within the coal particle is transferred from the internal structure to the external environment by steam pressure-driven jet flow [13]. The jet flow will destroy the pore structure of the coal particles, improving the grindability of coal.

Microwave heating has a number of advantages over conventional heating, including rapid heating, quick starting and stopping, high-energy efficiency, and superior dried-product quality [14]. Hence, microwave irradiation can be applied to coal pyrolysis or coal desulfuration [15–17]. Meanwhile, many researchers have focused on improving the grindability of minerals by microwave irradiation. Marland et al. [18] showed that microwave irradiation has a positive effect on the grindability of different coal ranks and no detrimental effect on the fuel potential of the coal. Low-rank coals were sensitive to microwave irradiation and the maximum increment on their grindability was 50%. They believed that the controlled mechanisms for improving the grindability of coals by microwave irradiation included the changing phase of the inherent moisture within the coal matrix under considerable pressure and differential expansion by gangue mineral components. Lester [19,20] studied the effects of high-power microwave irradiation on the grindability and chemical and petrographic characteristics of different types of coal. The results revealed that the breakage rates of microwave-treated coals were incremental and that the grindability of microwave-treated coals was improved. Given that the residence time was short, the effects on the petrographic and chemical characteristics of treated coals were considered negligible. Sahoo [21] focused on the effect of microwave irradiation on the grindability of high-ash Indian coal. The results showed that microwave irradiation could induce micro fractures in the coal samples and increase their crystallinity. Therefore, the calculated Hardgrove grindability index and specific breakage rate of the treated coal samples increased and the Bond work index decreased. Samanli [22] investigated the effect of microwave treatment on grinding different high-moisture lignite coal samples. The breakage rates, Hardgrove index value, and amounts of fine ground products of microwave-treated coals increased. Microwave treatment had a more favorable effect on the coarse samples than on the fine samples.

Given that the moisture within the coal matrix has a high loss factor, the initial moisture of a coal sample has an important effect on the improvement of coal sample grindability under microwave irradiation. Moreover, the amount and particle size distribution of fine ground product for <0.154 mm particle size have direct effects on the economy and slurrying ability of coal water slurry prepared with lignite. Therefore, the effects of microwave irradiation time, particle size range, and initial moisture on the grinding characteristics of untreated and microwave-treated XLs were investigated in this study. The mass fraction and particle size distribution of fine ground products with <0.154 mm particle size range of untreated and microwave-treated XL were obtained. The controlled improvement mechanisms of the grindability of XL under microwave irradiation were discussed by analyzing the proximate analysis, scanning electron microscopy (SEM) and nitrogen absorption results of untreated and microwave-treated lignite coals. The goal is to provide references for processing and utilizing XL.

2. Experimental

2.1. Material

The lignite used in this study came from the Ximeng region of Inner Mongolia, which is the largest producer of lignite in China. Naturally dried XL was crushed by using a jaw crusher and then screened into three different mono size ranges (1.00–1.70, 1.70–2.36, and 2.36–4.75 mm) by a standard sieve. To obtain the different initial moisture of XL, the XL for 1.70–2.36 mm particle size range was dried in an oven at 45°°C for 1 and 5 h. The dried XLs were named as 1.70–2.36 (1 h) and 1.70–2.36 (5 h) mm, respectively. Therefore, the increasing order of the initial moisture of XL is 1.70–2.36 (5 h), 1.70–2.36 (1 h), and 1.70–2.36 mm.

2.2. Methods

2.2.1. Microwave-drying experiments

Microwave-drying experiments were performed in a domestic microwave oven (EG923KX1-NAH, Midea, China) with a microwave frequency of 2.45 GHz. During the microwave-drying experiments, 100 g XL was uniformly spread in a 1000 ml plastic beaker and then placed at the center of a microwave oven. The XL was irradiated at a constant microwave power level of 900 W. The effects of microwave irradiation time (i.e., 0.5 and 3 min), particle size range ((i.e., 1.00–1.70, 1.70–2.36, and 2.36–4.75 mm), and initial moisture (i.e., 1.70–2.36 (5 h), 1.70–2.36 (1 h), and 1.70–2.36 mm) were investigated. The XLs that were irradiated for 0.5 and 3 min were named MI-0.5 min and MI-3 min, respectively. The microwave-treated XLs were cooled to room temperature naturally and then sealed and stored in a dryer. The microwave-drying experiments were conducted under air atmosphere.

2.2.2. Grindability tests

A frequency conversion planetary ball mill (XQM-2L, Nanjing Kexi Instruments Research Institute, China) was used to grind both the untreated and microwave-treated XLs. During the grindability tests, 20 g XL was uniformly spread in a 500 ml steel cylinder with six 2 cm-diameter steel balls that freely moved up and down at the designed operating speed. The revolution velocity of the grail was 420 rpm and the rotation velocity of the steel cylinder was 80 rpm. The grinding times of the XL were set to 0.2, 0.5, 1.0, 1.5, and 2.0 min, respectively. Thereafter, the ground products were sieved to five different particle size ranges (i.e., <0.154, 0.154–1.00, 1.00–1.70, 1.70–2.36, 2.36–4.75 mm) with the help of a sieve shaker for 5 min. Each particle size range was weighed, and the mass fraction was calculated.

The breakage rates of material (S_i) can be used to evaluate its grindability and be connected with the Hardgrove grindability index [19–22]. A higher breakage rate corresponds to better grindability. The breakage rates of the coal samples were different for each particle size. Once an effective breakage occurs in the mill, the breakage rate can be modeled on the basis of the first-order grinding kinetics. When considering only the top size fraction of each particle size range, the simplest expression that can be used to calculate the breakage rate S_1 is shown in the following equation [20]:

$$\ln\left(\frac{w_1(t)}{w_1(0)}\right) = S_1 \times t, \tag{1}$$

where t is the grinding time (min), $w_1(0)$ is the relative amount of the top size particles in the mill at time = 0 and is 100% in this case, $w_1(t)$ is the mass fraction of the top size particles in the mill at time t (%), and S_1 is the breakage rate of the top size particles of each particle size range (min^{-1}). Therefore, breakage rate S_1 can be calculated by plotting the natural logarithm of the relative amount of top size particles against the grinding time, and the slope of the straight line should be equal to S_1.

2.2.3. SEM, nitrogen absorption and particle size distribution experiments

The surface micro-topography of the XLs was measured by SEM (SIRION-100, FEI, The Netherlands). The microscopic pore structure of XL was determined with an ASAP 2010 automatic surface area and pore analyzer. The particle size distribution of fine ground product was obtained with a Mastersizer 2000 laser particle size analyzer.