Fuel 162 (2015) 305–312

Contents lists available at ScienceDirect

Fuel

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

# Effects of different drying methods on the grinding characteristics of Ximeng lignite

Jie-Feng Zhu, Jian-Zhong Liu *, Jun-Hong Wu, Jun Cheng, Zhi-Hua Wang, Jun-Hu Zhou, Ke-Fa Cen

*State Key Lab of Clean Energy Utilization, Zhejiang University, Hangzhou 310027, China*

## HIGHLIGHTS

- Microwave drying has the most remarkable effect on lignite grindability.
- Combined drying has no advantages in improving lignite grindability.
- Moisture removal and physical structure damage improve lignite grindability.
- Energy saving can be achieved when lignite is irradiated for a short period.

## ARTICLE INFO

*Article history:*
Received 19 July 2015
Received in revised form 7 September 2015
Accepted 12 September 2015
Available online 25 September 2015

*Keywords:*
Lignite
Microwave drying
Conventional drying
Grindability
Breakage rate

## ABSTRACT

Ximeng lignite (XL) was treated by using different drying methods, namely, conventional, microwave, and combination, to investigate their effects on the grinding characteristics of XL. The controlled mechanisms that improved the grindability of XL treated by different drying methods were analyzed with proximate analysis and scanning electron microscope. Results showed that the removal moisture and the physical structure damage induced by thermal stress or steam jet flow improved the grindability of treated XL. Microwave drying had the most remarkable effect on the grindability of XL. The increments in grindability of XL irradiated for 0.5 and 3 min were 44.03% and 200.45%, respectively. Compared with conventional dying, combined drying simultaneously improved grindability of XL, and reduced energy consumption. However, combined drying reduced the effects of microwave drying on the increment in the grindability of XL. Drying treatment for a short period could not effectively increase the mass fraction of finely ground product unless drying time was properly prolonged. According to the economy evaluation at lab scale, treatment of XL by microwave drying for a short period improved the grindability of treated XL and achieved a maximum energy saving of around 10% after a long period of the grinding process.



## 1. Introduction

China has abundant lignite resources. Lignite reserves are approximately 130 billion tons, which account for 13% of total coal reserves. Proven lignite reserves in Inner Mongolia account for 77.55% of the total lignite reserves in China [1]. However, lignite sources in China have not been sufficiently developed and utilized. Lack of relevant research has negatively affected the efficient utilization of lignite sources in China economically and environmentally. Hence, a study on various properties of Ximeng lignite (XL) will allow for better utilization of China's lignite resources.

Despite consumption of large amounts of energy and having a direct connection with the economy of coal utilization, comminution of raw coal is a necessary process prior to further utilization. Generally, several factors, such as rank, moisture content, petrography, and distribution and types of minerals, affect the hardness of coal [2]. Grindability is greatly reduced if the moisture content of coal is higher and its coal rank is lower [3]. To utilize XL cleanly and efficiently, dehydrating XL is necessary prior to its deep processing and further utilization.

The pre-heating treatment of the coal sample can induce structural micro-fractures in coal, which will then reduce the amount of energy required by a mill to achieve the same grind size and increase the throughput of the mills [4]. Therefore, many drying methods, including conventional, microwave, and waste-heat gas, are used to dehydrate coal to increase grindability of coal sample [5–8]. Since the 1920s, conventional drying has been used in the grinding of minerals [9]. However, energy consumption of conventional drying is higher than the saved energy by increasing the

* Corresponding author. Tel.: +86 571 87952884; fax: +86 571 87952443.
*E-mail address:* jzliu@zju.edu.cn (J.-Z. Liu).

http://dx.doi.org/10.1016/j.fuel.2015.09.028

grindability of coal samples. Therefore, conventional drying is unlikely to be an economically acceptable method based on total energy requirements [10].

Heating mechanisms between conventional and microwave drying methods are fundamentally different. During conventional drying, heat transfers from the drying medium to the surface of sample through conventional heat transfer mechanisms, i.e., through conduction, convection, and radiation. Then, heat transfers from the surface of the sample to the internal part through conduction, which gradually increases the temperature of the sample. As energy transmission efficiency of conventional drying is relatively low, a considerable amount of time is inevitably required. Moreover, extended heating may have negative effects on the sample itself, e.g., oxidation and loss of volatile features. Hence, conventional drying is not an attractive option. During microwave drying, polar molecules of the coal sample under microwave irradiation cause dipoles or ions to align within the applied high-frequency alternating electric field. As the applied alternating electric field oscillates, the aligned dipoles or ions attempt to realign themselves. This movement causes energy loss in the form of heat through molecular friction or dielectric loss, which raises the temperature of the coal sample and dries the material [11]. Microwave is a form of electromagnetic energy that can permeate into the internal part of the coal sample. The process volumetrically heats the coal sample. However, not all materials can absorb microwave energy and then be heated under microwave irradiation. Materials are classified into three groups according to their interaction with microwaves; these three groups are conductors, insulators, and absorbers [12]. Conductors can reflect microwaves without any penetration, insulators are transparent to microwaves without any absorption, and absorbers absorb and dissipate microwaves into heat depending on the value of the dielectric loss factor [13].

The loss factor for organic macromolecular structures in coal is low, which means that coal matrix as bulk material cannot easily absorb microwave energy [14–16]. However, other phases within the coal matrix, such as moisture and some mineral impurities (such as pyrite), have higher loss factor. Therefore, moisture and pyrite are more effective in microwave heating than the rest of the coal matrix and thus heat at a faster rate [17,18]. Coal matrix selectively absorbs microwave energy in the microwave field because of its anisotropy. The differential heating of each phase within coal matrix causes thermal stresses and therefore induces fractures within coal particles, which is good for increasing the grindability of coal. In addition, moisture within coal matrix evaporates after absorbing microwave energy, and the steam pressure field is quickly established within coal particles. Therefore, moisture within coal particles is transferred from the internal structure to the external environment through steam pressure-driven jet flow [19]. The jet flow destroys the pore structure of coal particles, which increases the grindability of coal.

Pre-heating methods, including conventional and microwave drying, have different effects on the grindability of coal sample. Marland et al. [7] compared the grindability of microwave-exposed coals to conventionally heated coals. The grindability of coal sample treated at 250 °C for 60 min could be increased about 20%, and similar results could be achieved when the coal sample was treated for 3 min under microwave irradiation. Obviously, the effect of microwave drying on the increment in grindability of coals was more remarkable than that of conventional drying. The inherent moisture within the coal structure-changing phase under considerable pressure and the differential expansion by gangue mineral components were responsible for the increment in grindability of coals under microwave irradiation. Lytle et al. [8] investigated the effects of pre-heating on the grindability of coal. Population balance grinding models were used to interpret results of grinding coal before and after preheat treatments. Simulations of locked cycle tests showed that a 40% increase in grindability could be achieved. Lester et al. [4,20] paid attention to high-power microwave treatment of coals for very short residence times. The grindability, physical, and petrographic characteristics of microwave-treated coals were investigated. The high-power microwave treatment of coals for very short residence times could still induce physical changes, such as cracks and fissures, and thus increased breakage rate of coals. As the residence times were very short, the effects on petrographic and chemical characteristics were considered negligible. Samanli [21] found that the breakage rate and the amount of finely ground products of lignite with high moisture increased under microwave irradiation. The effect of microwave treatment on grindability was relatively more favorable for coarser particles than for finer particles.

Combined drying technologies are considered a good option to simultaneously improve the quality of dry samples and reduce energy consumption [22]. Combined microwave-convective drying has been widely investigated in various technological and scientific fields, such as the food, agricultural, and chemical industries [23–28]. During combined microwave–convective drying, the sequence of different drying methods has an important effect on the drying characteristics of the sample. Therefore, two different combination patterns (i.e., microwave–convective and convective–microwave drying) should be separately considered. Although combined microwave–convective drying has been reported to dehydrate and modify lignite, few researchers pay attention to whether combined microwave–convective drying can economically improve grindability of lignite.

XLs were processed and dehydrated using different drying methods [i.e., conventional drying (CD), microwave drying (MD), conventional–microwave drying (CD–MD), and microwave–conventional drying (MD–CD)]. Effects of different drying methods on the grindability of XL were investigated. The controlled mechanisms of increment of grindability of XL treated by different drying methods were discussed according to proximate analysis and the use of scanning electron microscope (SEM). In addition, the economy of increment of grindability of XL treated by different drying methods was analyzed. The goal of this study is to provide references for processing and utilizing XL.

## 2. Experimental

### 2.1. Materials

Lignite used in this study came from the Ximeng region in Inner Mongolia, China. Naturally dried XL was crushed by using a jaw crusher and screened into the required mono size fraction, i.e., −2.36 + 1.70 mm, by using a standard sieve.

### 2.2. Methods

#### 2.2.1. Microwave drying experiments

A domestic microwave oven (EG923KX1-NAH, Midea, China) with a microwave frequency of 2.45 GHz was used to perform microwave-drying experiments. The rated power input of microwave oven is 1450 W and is used to evaluate the economy of microwave drying. During the microwave drying experiments, 100 g XL was uniformly spread in a 1000 ml plastic beaker and then placed in the center of the microwave oven. XL was irradiated at a maximum microwave power level of 900 W. The effects of microwave irradiation time (i.e., 0.5 and 3 min) were investigated. XLs irradiated for 0.5 and 3 min were named MD-0.5 min and MD-3 min, respectively. Microwave-treated XLs were cooled to room temperature naturally and were sealed and stored in a dryer. The microwave drying experiments were conducted under air atmosphere.