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Thin-layer drying characteristics and modeling of Ximeng lignite under microwave irradiation

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ABSTRACT

The thin-layer drying characteristics of Ximeng lignite (XL) were investigated under microwave irradiation, and mathematical modeling using thin-layer drying models from literature was performed. The effects of coal particle size and microwave power level on drying characteristics were studied. The drying rate increased and drying time decreased with increasing particle size or microwave power level. The drying rate and drying rate to moisture ratio curves, which contained a constant rate period at lower microwave output powers, exhibited fast heating and falling rate periods at different coal-particle sizes and microwave output power levels. Among the 14 thin-layer drying models proposed, the Midilli–Kucuk model provided a better fit for all applied drying conditions and could be used to estimate moisture in XL at any time during the microwave-drying process after running a multiple regression analysis. The drying rate constants and apparent diffusion coefficients (determined from the Midilli–Kucuk model and Fick's second law, respectively) increased with increasing particle size or microwave power level. The activation energy estimated from a modified Arrhenius equation was $E_a = 77.0485$ W/g. The equilibrium moisture of XL decreased with increasing microwave output power or decreasing particle size.

1. Introduction

Presently, global energy consumption heavily relies on fossil fuel, which accounts for 87% of energy consumption. Oil dominates the fossil fuels; however, coal is the fastest-growing fossil fuel. In 2012, coal accounted for 29.9% of global energy consumption and China accounted for 50.2% of global coal consumption [1]. Because of increasing coal consumption, high-rank coal, such as anthracite and bituminous, is in short supply. Therefore, there is increased interest in utilizing low-rank coal, such as lignite.

China has abundant lignite resources, with about 129 billion tons of proven lignite reserves, which account for about 12.69% of total coal reserves [2]. Because of lignite's high moisture and low fixed carbon content, its calorific value is low. Lignite weathers easily and suffers from spontaneous combustion owing to its high volatile content; hence, it is not suitable for long-distance transport and storage [3]. Most lignite is used as fuel in nearby power plants or as raw material in the chemical industry. The use of lignite in practical applications has several disadvantages, including low energy efficiency, environmental pollution, and high costs.

In order to utilize lignite resources cleanly, efficiently, and at a reduced cost, it is important to dehydrate and modify lignite prior to its deep processing and further utilization [4,5]. Although many kinds of drying methods have been developed because of lignite's high moisture, successful reduction of energy consumption and drying costs, among other goals, remains to be achieved. The dehydration process of lignite can be classified into two categories: evaporation drying and non-evaporation drying [6].

During evaporation drying, heat equal to the latent heat of water evaporation is added to the coal sample either directly or indirectly; moisture within the coal is then gasified and removed. Evaporation drying methods include the coal mill dryer [7,8], flue gas drum dryer or fluid bed dryer [9], steam-fluidized bed dryer [10], microwave drying [11,12], solar drying [13], and so forth.

During non-evaporation drying, moisture is removed from the coal sample in liquid form. Therefore, the latent heat of water evaporation is saved and the emission of greenhouse gases is reduced; however, non-evaporation drying is usually done using high temperatures and high pressure. Methods of non-evaporation drying include mechanical thermal expression [14,15] and hydrothermal dewatering [16,17].

During the microwave-drying process, the 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 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 [18].

Because of microwave heating's unique features (such as selective heating, volumetric heating, and instantaneous heating), it offers a

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number of advantages compared with conventional heating: (i) rapid heating; (ii) energy transfer instead of heat transfer; (iii) uniform heating; (iv) enhanced moisture loss; (v) quick starting and stopping; (vi) greater safety and automation; and (vii) superior dried-product quality [19]. Due to these unique features, microwaves have been widely used to heat or dry materials in various technological and scientific fields, such as the food industry, light industry, chemical industry, and agricultural industry[20,21]. Furthermore, microwaves have been used in mineral processing to improve grindability, to decompose or dehydrate minerals, and so on [22,23]. These unique features also make microwave heating an effective method of dehydrating and modifying lignite.

Investigating the use of microwaves in Inner Mongolia lignite dehydration is important because proven lignite reserves in Inner Mongolia account for 77.55% of the total lignite reserves in China; thus, an investigation of Inner Mongolia lignite dehydration will allow for better utilization of China's lignite resources.

In order to systematically investigate the microwave-drying characteristics of Ximeng lignite (XL) and to analyze moisture migration during the drying process, this paper investigates the thin-layer drying and reabsorption characteristics of XL at different coal particle sizes and microwave power levels. The goal is to provide references for processing and utilizing XL.

2. Experimental

2.1. Material

This study used lignite from the Ximeng region in Inner Mongolia, which is the largest producer of lignite in China. Naturally dried XL was ground in a bowl mill and sieved to four different coal particle-size fractions (less than 154, 154 to 600, 600 to 1000, and 1000 to 1700 μm). The sieved coal powder was sealed and stored. To determine the initial moisture of coal samples at different particle sizes, three 2 g XL at each particle size were dried in an oven at 105 °C for 2 h. Results from each of the three samples were averaged together to reach the data shown in Fig. 1. Proximate and ultimate analyses of the raw coal sample (less than 154 μm) can be found in Table 1. The ash content and composition of coal sample with different particle sizes are shown in Table 2.

2.2. Methods

2.2.1. Microwave-drying experiments

Microwave-drying experiments were performed in an atmospheric-pressure microwave reaction workstation (MAS-II; Sineo Microwave Chemistry Technology Ltd., Shanghai, China) with a microwave frequency of 2450 MHz (a wavelength of 12.24 cm). The microwave workstation is capable of operating at eight different microwave output power levels: 300, 400, 500, 600, 700, 800, 900, and 1000 W. The workstation is equipped with a non-contact infrared thermometer and, using frequency conversion, the power level is automatically adjusted for temperature. The processing time is adjusted and displayed with the aid of a digital-control facility located on the microwave workstation.

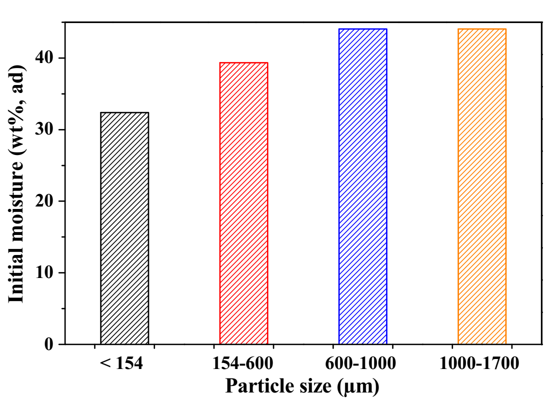

Fig. 1. Initial moisture of coal samples with different particle sizes.

Table 1
Proximate and ultimate analyses of XL.

Proximate analysis (%)				$Q_{net,ad}$	Ultimate analysis (%)				
M_{ad}	A_{ad}	V_{ad}	FC_{ad}	(J/g)	C_{ad}	H_{ad}	N_{ad}	$S_{t,ad}$	O_{ad}
32.39	15.84	24.75	27.02	17355	41.52	2.99	0.62	0.6	6.04

M_{ad}, A_{ad}, V_{ad} and FC_{ad} refer to the moisture, ash, volatile and fixed carbon content on an air dried basis, respectively; $Q_{net,ad}$ refers to the net calorific value on an air dried basis.

During microwave-drying experiments, each sample was put in a glass Petri dish (diameter of 71 mm, height of 15 mm) and placed in the center of the workstation. Moisture loss was measured in 1-min intervals by taking out the glass Petri dish from the workstation and weighing it on a digital balance (Sartorius BS 224S, with a precision of 0.1 mg). The total microwave applied time was 10 min. To obtain the temperature history of the drying process, sample temperatures were measured with a hand-held infrared thermometer (GM700, Benetech, Shenzhen, China, with a precision of ±1.5% °C within the range of <700 °C) between the time the microwave was shut down and the time the sample was removed to be weighed. Each experiment was replicated at least three times and average measurement values were used for statistical analyses. The reproducibility of the drying experiments and temperature-measurement experiments were within the range of ±3.25% and ±13.02%, respectively. All weighing processes (including temperature measurement) were completed in less than 12 s during the drying process.

To investigate the effect of coal particle size on the drying characteristics of XL, four different coal particle-size fractions (i.e., less than 154, 154 to 600, 600 to 1000, and 1000 to 1700 μm) were periodically irradiated at a constant microwave power level of 500 W using 5 g XL. In order to investigate the effect of microwave output power on the drying characteristics of XL, three different power levels, namely, 300, 500, and 700 W, were used for drying 5 g XL with particle sizes of 154 to 600 μm.

2.2.2. Moisture reabsorption of dried coal sample

The effects of coal particle size and microwave power level on the moisture reabsorption performance of coal sample were investigated. A 2 g processed XL was placed into an atmosphere with constant temperature and humidity (temperature of 30 °C, relative humidity of 70%), and the moisture reabsorption of coal sample was studied. The samples" mass changes were recorded for 130 h.

2.3. Mathematical modeling

In order to determine the moisture ratio as a function of drying time, the moisture data obtained from the drying experiments were curve fitted to find the most suitable model among 14 different expressions proposed by earlier authors (Table 3).

Table 2
The ash content and composition of coal sample with different particle sizes.

Particle-size fraction (μm)	A_{ad} (%)	Ash composition (%)						
		SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O
<154	15.84	62.08	13.67	5.09	3.09	7.19	0.92	1.49
154–600	12.72	54.63	14.09	6.52	5.42	6.85	1.05	2.33
600–1000	9.23	46.65	14.86	6.26	6.96	7.64	1.12	3.01
1000–1700	8.55	45.35	15.48	4.80	9.03	6.40	1.26	3.12