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Microwave drying performance of single-particle coal slime and energy consumption analyses

Zhanlong Song, Chuanming Jing, Liansheng Yao, Xiqiang Zhao *, Wenlong Wang, Yanpeng Mao, Chunyuan Ma

National Engineering Laboratory for Coal-fired Pollutants Emission Reduction, Shandong Provincial Key Lab of Energy Carbon Reduction and Resource Utilization, Shandong University, Jinan 250061, China

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ABSTRACT

The drying of coal slime with high moisture is an essential step for the majority of its industrial applications. Microwave radiation could serve as an alternative way of efficient drying, owing to its unique heating properties. In this study, the weight loss and temperature distribution of spherical single-particle coal slime were measured by using a microwave thermogravimetric analysis (MTGA) device, which was designed for this study, equipped with an accurate electronic balance and fiber optic thermometers. In addition, the effects of microwave power (320, 480, 640, and 800 W) and particle size (30, 40, 50, and 60 mm) on the drying performances were studied. The microwave drying process of coal slime comprises three stages: an incubation period, whereby a rapid increase in temperature occurs, a constant-rate drying stage, during which a rapid moisture loss occurs at about 100 °C, and a falling-rate drying period, during which a significant increase in temperature is observed again. Weight loss rates increased with increasing power output of the microwave oven or with decreasing particle size. The energy consumption and the energy efficiency during the drying process were also analyzed. The results demonstrated that the specific energy consumption declined with the overall increase in power and particle size, while the efficiency of microwave output increased with increasing particle size. Furthermore, the diffusion kinetics of moisture in coal slime were examined. The effective diffusion coefficients of moisture increased with both increasing particle size and microwave power, whereas the activation energy of the diffusion process decreased with increasing particle size.

1. Introduction

Coal slime is a by-product of coal washing and cannot be utilized on large volumetric and temporal scales owing to its high levels of humidity, and high adhesion and low heat value properties, which may lead to significant energy dissipation and potential environmental pollution. There is an urgent need for its large-scale utilization, and to achieve this, the quality improvement of coal slime through efficient and environmentally friendly drying methods is essential.

Currently, the most commonly used drying system is the rotary dryer; however, this system requires additional hot gases as the source of heat, which means that large capital costs are required, and involves technical complexity combined with the addition of a gas clean-up unit. In addition, volatile material is readily released as a result of the high temperature treatment, which may degrade the quality of samples and sharply increase their potential risk of combustion and explosion. Apart from rotary dryers, dryers that use superheated steam as their drying medium are often discussed. Despite the high level of safety, however, seeking for the proper steam sources usually limits the wide application of these drying technologies; it is also difficult to achieve a deep dehydration with the moisture content as low as less than 10%.

In conventional drying, the drying rate usually decreases with decreasing rate period owing to the low drying efficiency caused by the large resistance of moisture diffusion from the interior region to the surface of the samples. As a result, the total drying time may be significantly prolonged and the energy consumption will be substantially increased.

Microwave heating has several unique features related to selective and volumetric heating compared to the traditional approaches. Firstly, microwave can selectively couple with materials having high loss factors like water, and therefore particles with higher moisture tend to absorb more microwave energy. In addition, a more uniform temperature distribution and a better energy transfer can be achieved in volumetric heating resulting from the direct microwave-material interactions. Moreover, the significant internal evaporation generated by internal heating will lead to a substantial increase of moisture transport and noticeably increase the drying rate, especially at the falling rate drying period. This featured heating scheme rarely occurred in conventional drying. Moreover, the microwave energy transfer will decrease as the evaporation approaches completion, which will result in automatic moisture leveling; therefore, it may be possible to minimize overheating of the surface of the samples, which usually occurs in traditional drying.

* Corresponding author.
E-mail address: zxq@sdu.edu.cn (X. Zhao).

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Subsequently, in the microwave drying process, low operation temperatures, expected energy saving, good product quality, low generation of fugitive dust and excellent safety potential will be encountered simultaneously.

With regard to the above features of microwave, in recent years, microwave technology has been widely researched and it has been applied in the drying of food [1] as well as in the wood [2,3] and mining industry [4] as an efficient and clean source of heat. The research on coal dehydration using microwaves has been increasing in recent years [5–13]. Although a considerable number of studies have been carried out on microwave drying of low rank coal, such as lignite and sub-bituminous coal, there is a severe paucity of data regarding the fundamental microwave drying of coal slime [14]. The studies that focused on the dewatering of coal slime are very significant, not only because they contribute to the advancement of the basic knowledge of the coal slime drying but also because it helps to boost the industrial application of this new technology by using microwave radiation as a heat source.

The weight and temperature of samples are important factors affecting the drying performance of samples. However, the measurement of temperature and weight loss during the microwave drying process are mostly performed in an intermittent manner (i.e., the heated samples after a certain period of drying were usually taken out of the microwave oven in order to carry out temperature and weight loss measurements [6,8–10,13]). This may give rise to thermal hysteresis and difficulty in obtaining the actual drying data, even resulting in the loss of some key data relevant to the drying kinetics. The errors will possibly be enlarged under microwave radiation because its heating rates are faster than those of traditional heating. For such analyses, the continuous measurement of temperature is preferred and most scholars frequently use infrared thermometer or thermocouple to measure the temperature during microwave drying tests. Nevertheless, the infrared thermometer can merely be used to measure the sample surface temperature. Under microwave heating, however, the surface temperature is usually lower than the temperature in the interior areas, owing to the internal heating principle. This possibly leads to the degeneration of the quality of coal due to the uneven heating of the sample (e.g., overheating). Thus, this method cannot detect the comprehensive temperature distribution, both on the surface and in the interior of the samples. Furthermore, the surface temperature is frequently influenced by the emittance of the samples used, which often changes during the drying and thus, it is difficult to measure it directly. On the other hand, the thermocouple or thermal resistance is not likely to be used in the microwave field directly, because of its severe interference with microwave radiation, (i.e., the potential generation of electrical discharge between the metal material and the microwave radiation).

Based on the scarcity of research on microwave drying of coal slime and the difficulties in microwave heating research, the current study presents a featured method, named Microwave Thermogravimetric Analysis (MTGA), in order to carry out an all-round research on the microwave drying performances of coal slime. The MTGA achieved the real-time measurement of sample weight loss under microwave radiation. Moreover, several fiber optic thermometers, which were not affected by microwave field and could measure temperature more accurately, were applied in the present experimental system to acquire the online temperature, not only on the surface area, but also in the interior of the coal slime samples. The use of this new means of MTGA can even be extended to many other fields, such as combustion, sintering, catalysis and synthesis of coal; it can also be used to study the chemical reaction of other materials, such as chemicals and minerals, biomass and other solid wastes. Taking single grain slime as the research object, this paper mainly studied the drying characteristics of coal slime under different microwave powers and at varied particle sizes. Kinetic parameters, as well as energy consumption and utilization efficiencies of the drying process, were also analyzed. The work aimed at elucidating the drying mechanism and kinetic characteristics of coal slime subjected to microwave radiation and it provided instructive data for the design of industrial scale microwave dryers for coal slime, as well as other wet materials.

2. Experimental

2.1. Materials

The fine coal slime was collected from Bucun coal mine at Jinan, China, and the results of its proximate analysis are listed in Table 1. A specified mass of coal slime was initially weighed out and then spherical particles of different sizes (30, 40, 50 and 60 mm) were created. Prior to this, preliminary tests were carried out to obtain the relationship between the sample mass and particle size. A replication of the tests showed that the sample masses of 19.5, 46.0, 90.0, and 156.0 g corresponded to the particle sizes of 30, 40, 50, and 60 mm, respectively.

2.2. Methods

A schematic diagram of the microwave drying system was shown in Fig. 1. A domestic microwave oven (Frequency 2.45 GHz, maximum power 800 W) was modified by adding a temperature and weight measurement system and a data acquisition system for MTGA. The G&G500 digital balance was used to continuously record the sample mass during the drying process, with an accuracy of 0.01 g. The GX-1 fiber optic sensors, which had a measuring range of 0–200 °C, were also applied to detect the in-situ temperature of the sample in varied points from the surface to the internal parts, as shown in Fig. 2.

When the weight loss tests were performed, samples with different particle sizes were first placed on the bottom center of a plastic tray with a diameter of ~100 mm; then, the sample and the tray were both put in the microwave oven and suspended from the balance through a fine thread, which passed through a 6 mm-diameter hole in the top center of the cavity. As the plastic tray and fine thread are poor absorbers of microwave energy, the influence on the sample weight measurement could be ignored. Then, the microwave drying tests started at microwave powers of 320, 480, 640, and 800 W. At the same time, the data acquisition system was in operation to record the weight changes during the drying process at 10 s intervals until the weight loss of the sample almost ceased. When testing the influence of different microwave powers on the drying characteristics, the sample size was kept constant at 50 mm, while the microwave power was kept constant at 800 W in order to investigate the influence of different particle sizes on the characteristics of trying.

Temperature measurements were carried out under the same conditions as those used in the weight loss tests. In order to avoid the interference of temperature measurements on weight measurements, the measurements of weight and temperature were performed separately. In our tests, three fiber optic thermometers were employed to measure the temperature changes at different parts of the sample (Fig. 2). It was noticed that the experiments would be terminated when the measured temperature reached 180 °C, due to the limited range of the thermometers used. By coupling the measurement values of weight loss and temperature changes, the integrated drying performance could be obtained. This could explain thoroughly the drying mechanism. Each test was repeated three times, and the average was taken in order to avoid possible discrepancies.

Table 1
The proximate analysis of samples (on as-received basis).

M_t (%)	V (%)	A (%)	FC (%)	Low heating value (MJ/kg)
22.10	10.36	33.89	33.65	15.74

M_t, A, V and FC refers to the moisture, ash, volatile and fixed carbon content of the samples, respectively.