Fuel Processing Technology 156 (2017) 491–499

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Research article

Coal slime hot air/microwave combined drying characteristics and energy analysis

Zhanlong Song, Chuanming Jing, Liansheng Yao, Xiqiang Zhao *, Jing Sun, 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

ARTICLE INFO

Article history:
Received 30 June 2016
Received in revised form 27 September 2016
Accepted 11 October 2016
Available online 17 October 2016

Keywords:
Coal slime
Hot-air drying
Microwave drying
Combined drying
Energy consumption

ABSTRACT

The drying of coal slime with high moisture content is indispensable for the majority of its industrial applications. In view of the low drying rate at the falling-rate drying period during the conventional drying process, hot-air drying followed by microwave drying, a featured deep drying method, can fundamentally solve this problem and achieve fast and efficient dewatering. In this study, the combination of hot-air and microwave drying to dry coal slime was presented, the general behavior of combined drying method was investigated at a combined fixed bed reactor with hot-air in the temperature range of 120–200 °C and a microwave oven with a maximum power of 800 W. The critical point of hot-air drying, also termed transition point at which hot air drying switched into microwave drying, were experimentally determined and the results showed that the moisture contents of the critical points were about 15% for the samples used. Furthermore, the effects of different target moisture contents and microwave powers on the drying performance and energy consumption of combined dewatering were studied. The results showed that microwave drying could significantly elevate the drying rate when the coal slime reached the critical moisture contents during the hot-air drying method, which indicated that combined drying was an effective method to achieve deep drying of coal slime with a significant reduction in total drying time.

1. Introduction

Coal slime is a by-product of coal washing, and cannot be easily utilized on a large scale due to its high levels of moisture content, high viscosity, high ash content, and low heat value properties. In recent years, the amount of coal slime has increased drastically due to the fast rise in the amount of coal washing in China, which could potentially lead to significant energy waste and environmental pollution. Currently, the preferred means of utilizing coal slime is combustion as fuel for power generation [1]; however, the high level of moisture content may act as a dominating obstacle hindering its wide application, and potentially endangering the stable operation of the boilers. Consequently, the dewatering process of coal slime before burning is essential to lowering the moisture content and improving the heat values so that the coal slime has wider application with respect to economic, social, and environmental considerations.

Currently, coal slime drying methods can be divided into two categories: mechanical drying and thermal drying. Mechanical drying includes the processes of sieving, centrifugation, and filter press drying, but after mechanical drying, the moisture content is still relatively high (approximately 20%) [2] and fails to meet the requirements of most industrial applications. Thermal drying is required to further lower the moisture content. Presently, drying is achieved by direct or indirect contact between wet coals and a hot medium, such as hot air [3–6], high-temperature gas [7], or superheated steam [8–11].

Conventional thermal drying processes can generally be divided into the growing-rate (AB), constant-rate (BC) and falling-rate (CE) drying periods [12], as shown in Fig. 1. The AB segment represents the incubation of materials, during which the temperature of the material rapidly grows. During the BC period, the heat that the drying medium transfers to the material is entirely used for moisture vaporization. The temperature of the material surface and the water vapor partial pressure of the material surface are maintained at constant values so that the drying rate remains constant. The CE segment represents the falling-rate drying period, during which the material contains less moisture, and the rate at which moisture transfers from the inside to the surface is lower than the water vaporization rate of the material surface. During this time, the drying rate is controlled by the transmission rate of the moisture inside the material. Therefore, this period is also known as the internal migration control phase. As the moisture content of the material decreases, the rate of moisture migration within the material also

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

http://dx.doi.org/10.1016/j.fuproc.2016.10.016
0378-3820/© 2016 Published by Elsevier B.V.

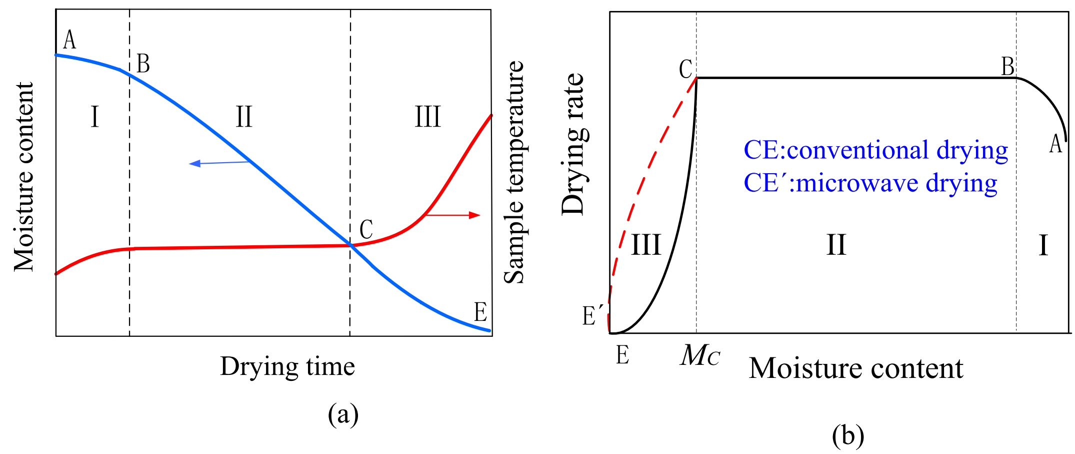

Fig. 1. Drying curves of materials under constant drying conditions [12]. I. Incubation period; II. Constant-rate drying period; and III. Falling-rate drying period.

gradually decreases such that the drying rate continues to drop. As shown in Fig. 1b, point C is the cut-off point between the constant rate and falling-rate segments, and is called the critical point. The moisture content corresponding to the point is the critical moisture content M_C. As the integration of water and coal becomes increasingly close, the drying rate of coal slime shows a "concave" falling pattern. The time and energy consumption of this stage can account for two thirds of the total drying process, but the drying amount is only one third, or even less [12]. Thus, this stage has become the bottleneck restricting the overall drying effect. Improving the drying rate at this stage is the key to increasing the efficiency of coal slime drying. In addition, conventional drying of coal slime is likely to cause a phenomenon in which the material is dry on the outside but wet on the inside. The coal slime drying is uneven or excessively dried and pulverized, which can even cause a coal dust explosion [13,14]. Thus, the conventional thermal drying method is prone to poor drying performance, uneven drying, and security issues during the falling-rate drying period. Conventional drying methods cannot meet the safe, fast, low-power, and deep-drying requirements. There is an urgent need for a new drying method to specifically improve the whole drying process of coal slime.

Microwave heating has several unique features of selective and volumetric heating over the traditional approaches [12]. One key advantage involves the application of internal heating, the homodromous transfer of heat and moisture in samples during microwave heating results in highly efficient dehydration. Moreover, microwave heating is especially suitable for drying large-sized coal pieces, like coal slime, which usually exists in the form of agglomerates due to viscosity. In addition, much higher drying rates are expected because of the rapid evaporation of liquid water. Hence, the drying time may be significantly shortened compared with traditional drying methods.

With these distinctive features, microwaves have been widely used to heat or melt various dielectric materials in applications such as food processing [15,16], agriculture- and forestry-related industries [17], and mineral processing [18–20]. Research on coal drying using microwaves has been increasing recently [21–31], which confirmed that microwave heating is an effective way to dry coal; compared with conventional drying, microwave drying had distinct advantages, such as reduced overall time and increased drying efficiency [11]. Although considerable research have been performed on the 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 [32,33].

Based on the above characteristics of traditional drying and microwave drying, it is possible to re-enhance the drying rate if microwave assisted heating is used after the coal slime enters the falling-rate drying period in the conventional drying process. It is even possible to bring the coal slime in the falling-rate drying period back to the constant-rate drying stage, or change the falling-rate drying curve from "concave" to "convex" (microwave drying has this important characteristic [12]), as shown by the dotted line CE′ in Fig. 1b. This would improve the conventional drying capacity by 6 to 8-fold [12], thus greatly accelerating the coal slime drying process. Through a combination of hot air/steam and microwave drying methods, hot air can be used to pre-dry the coal slime to the critical moisture content, supplemented by microwave drying to achieve deep drying. While reducing the total energy consumption of the drying process by incorporating conventional thermal drying, which consumes relatively little energy, the combination of methods shortens the overall drying time and ensures drying quality through the fast and uniform heating characteristics of microwave drying. The combined drying method has the advantages of both drying methods, facilitating high efficiency, low energy consumption, and high-quality drying, and is therefore a promising new technology for coal slime drying.

The hot air/microwave combined drying method has been widely used in the food industry [34–37] and for drying metallurgical materials [38]. It has been found that the two combined drying methods not only shortens the overall drying time and improves the drying efficiency, but also ensures product quality [34–37]. While making high purity quartz sand, Li found that it was difficult for any single drying method to meet the energy-efficient requirements; the hot air/microwave combined drying method meets the requirements of high-purity quartz sand, while demonstrating high energy efficiency [38]. At present, no studies have reported the hot air/microwave combined drying of coal slime or other similar minerals.

Based on these considerations, this paper proposes a hot air/microwave combined drying technology program. Tests were conducted to obtain the essential characteristics of the combined drying process, in order to determine the critical moisture content range of hot air drying, and the effects of different targeted moisture content (M_T) and different microwave power (P) on the coal slime combined drying characteristics and energy consumption. This paper provides theoretical and statistical references for the design and industrial application of the combined drying process.

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 were created. Prior to this, preliminary tests