Fuel Processing Technology 125 (2014) 94–105

Contents lists available at ScienceDirect

Fuel Processing Technology

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

Ultrasonic sludge disintegration for improving the co-slurrying properties of municipal waste sludge and coal

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ARTICLE INFO

Article history:
Received 25 October 2013
Received in revised form 15 March 2014
Accepted 15 March 2014
Available online 16 April 2014

Keywords:
Municipal wastewater sludge
Waste disposal
Ultrasonic
Coal water slurry
Slurrying

ABSTRACT

The high water content and complex components of municipal waste sludge (or sludge) lead to increased difficulty and cost of handling sludge. Coal sludge slurry (CSS) technology blends sludge into coal water slurry to produce a new slurry fuel that can be combusted or gasified as a substitute for petroleum. Environmental problems caused by sludge can then be solved and combustible matter in sludge can be used. The poor slurryability of raw sludge, which resulted from its high water holding capacity, significantly increases the viscosity of CSS. In this study, sludge was pretreated by ultrasonic energy and then mixed with coal to prepare CSS. After ultrasonic pretreatment, sludge flocs were significantly disrupted and scattered, and their particle size greatly decreased. Thus, the water trapped by flocs was released. When the ultrasonicated sludge was used to prepare CSS, the released water acted as a lubricant to decrease friction and interaction among coal particles. When the specific energy input of ultrasonic increased from 0 to 30 with 75 kJ/g dry sludge at 190 W, the characteristic viscosity of CSS decreased by 27.54% and 41.04%, respectively. Ultrasonic significantly improved the slurryability of sludge, and thus, could enhance sludge disposal scale to a high level.

1. Introduction

Municipal wastewater sludge (or sludge) generated during wastewater treatment is a special mixture with complex compositions. Sludge is essentially the aggregation of the microorganism zooglea and absorbed organic and inorganic matter. Aside from large amounts of water (>90%), numerous hazardous substances, including refractory organics, parasites, pathogenic microorganisms, heavy metals, and volatile matter are present in sludge [1–4]. Therefore, sludge has to be disposed of properly to ensure the normal operation and treatment efficiency of a wastewater treatment plant (WWTP) and to avoid secondary pollution [5,6]. With the sustainable development of the global economy and the constant progress of industrialization and urbanization, the continuous increase in sludge output and its safe disposal and reuse have raised sludge management cost, which accounts for 50% to 70% of the total operating cost of a WWTP [7]. Therefore, the disposal of large amounts of sludge through an economical and effective processing technology has become a universal concern among environmental protection industries today.

Coal sludge slurry (CSS) technology blends sludge into coal water slurry (CWS) to produce a new slurry fuel that can be combusted or gasified as a substitute for petroleum. Environmental problems caused by sludge can then be solved and combustible matter in sludge can be used during CSS application [8]. Researchers have shown that the ignition and burnout characteristics of coal–sludge blends are improved by the high content of organic substances and volatile matter in sludge [9,10]. Gerhardt and Spliethoff [11] studied the co-combustion characteristics of sludge with lignitous and bituminous coals. They found that the co-combustion of sludge and coal is feasible and economical based on the experimental results of boiler operation characteristics, thermal efficiency, flue gas emissions, and burning residue.

However, the viscosity of CWS was significantly increased after adding the untreated raw sludge. Consequently, the addition amount of sludge was limited. Li et al. [12] found that the rheological properties of CWS exhibited a significant change after adding sludge. In their study, the sludge dosage was 10 wt.% of the coal in CWS. Wang et al. [13] reported that CWS significantly increased in viscosity after adding sludge of 15 wt.% (sludge:coal). The maximum slurrying solid concentration was reduced by 9.5–12.5%. The primary objectives of CSS technology are to dispose of sludge at large-scale levels and to reduce the pressure of sludge on the environment. Therefore, predisrupting sludge is necessary to improve its slurryability and to enhance sludge mixing proportion in CSS. Wang et al. [14] adopted calcium oxide (CaO) to predisrupt sludge and studied the co-slurrying properties of CaO-modified sludge and coal. The results of their study showed that extracellular polymeric substances (EPS) of sludge were disintegrated to a certain extent. The viscosity of CSS decreased by 34% after pretreating the sludge with 3 wt.% CaO for 24 h.

Ultrasonic pretreatment is the most common method used for disintegrating sludge flocs. When sludge is exposed to ultrasound waves, gas bubbles are formed and grown under alternatively positive

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http://dx.doi.org/10.1016/j.fuproc.2014.03.014
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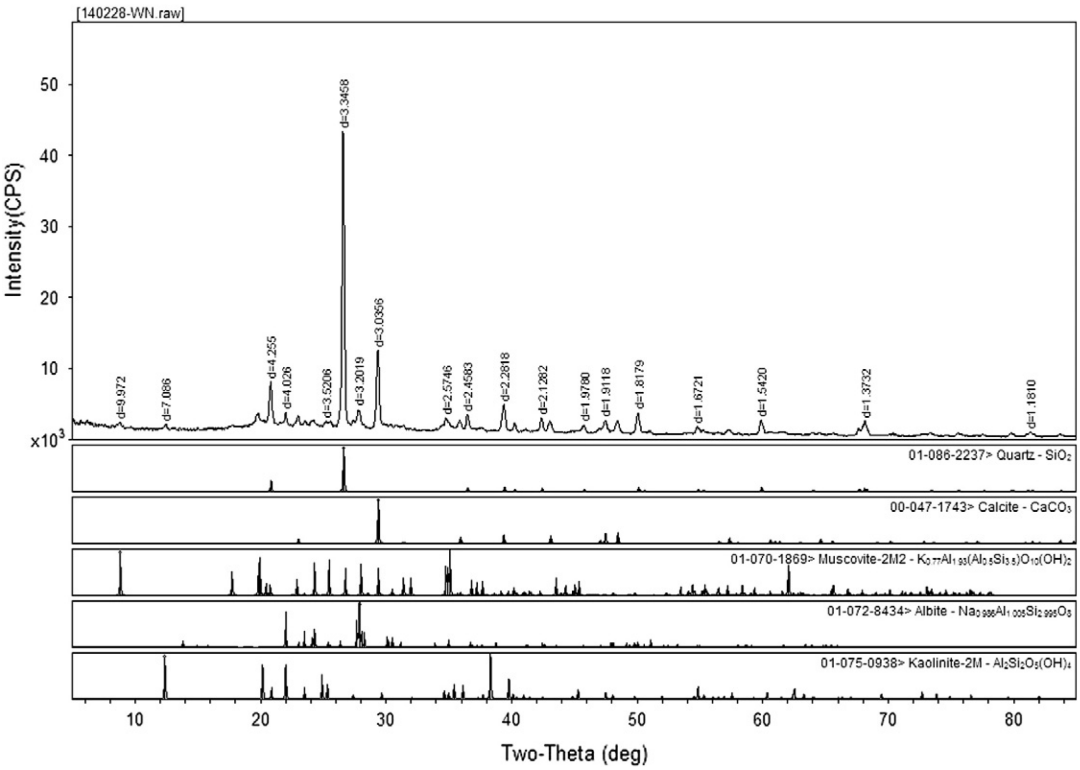

Fig. 1. X-ray diffraction analysis of raw sludge.

and negative presses caused by the acoustic energy. These bubbles can implode within a few microseconds, thereby resulting in very extreme local conditions of temperature (~5000 °C) and pressure (~500 bar) [15]. The powerful hydromechanical shear forces generated by bubble implosion can destroy the EPS and cell walls of microorganisms in sludge [16–19]. These extreme conditions can also lead to the generation of reactive radicals (e.g., •OH, HO_2•, and O•), which can degrade sludge flocs through sonochemical reactions [20]. Hydromechanical shear forces and sonochemical effects contribute to changing the physical, chemical, and biological properties of sludge. Bougrier et al. [16] applied ultrasonic energy of 1350 kJ/kg dry sludge (DS) to degrade sludge. The average particle size decreased from 31.99 μm to 18.50 μm, and the ratio of the soluble chemical oxygen demand (SCOD) to the total COD increased from 5.8% to 16.1%. Chu and Lee [18] showed that after ultrasonic pretreatment, the global structure of sludge transformed into a compact form and the surface charges became more negative.

The physicochemical properties of slurrying materials, including pore structure [21], particle size distribution [22], surface charges, and functional groups [23], have significant effects on slurrying properties.

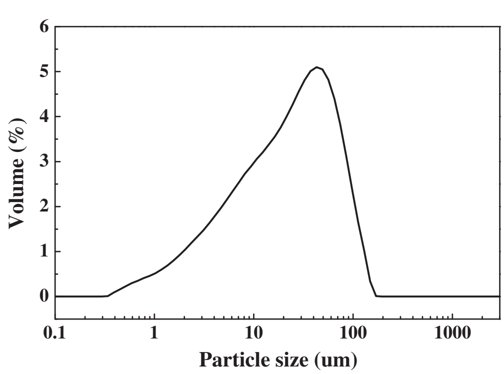

Fig. 2. The particle size distribution of coal.

However, only a few studies have been conducted on the slurrying properties of CSS, particularly no studies on improving the slurryability of sludge by ultrasonic pretreatment.

In this study, sludge was pretreated by ultrasonic disintegration. The pretreated sludge was mixed with coal, water, and additive to produce CSS. This study aims to (i) obtain more insight into ultrasonic sludge disintegration in terms of SCOD, soluble polysaccharide, soluble protein, particle size distribution, functional groups, moisture distribution, and floc microstructure; (ii) study the slurrying properties of CSS in terms of characteristic viscosity, as well as rheological and thixotropical properties; and (iii) examine the effects of different sludge disintegration degrees on slurrying properties.

2. Experimental

2.1. Materials

Sludge was collected from Qige WWTP in Hangzhou, China and stored in a refrigerator at 4 °C before use. SCOD, soluble polysaccharide, and soluble protein content of raw sludge are respectively 3.45 mg/g DS, 0.21 mg/g DS and 0.97 mg/g DS. Fig. 1 shows the X-ray diffraction analysis of raw sludge. From the analysis, raw sludge is mainly composed of quartz, calcite, muscovite, albite, and kaolinite.

Table 1
The proximate and ultimate analyses of the tested coal and sludge.

Sample	Proximate analysis (%)				Ultimate analysis (%)					Q_d
	M_t	A_d	V_d	FC_d	C_d	H_d	N_d	$S_{t,d}$	O_d	(MJ/kg)
Coal	3.56	19.15	31.53	49.32	65.86	4.43	1.14	1.38	8.04	26.42
Sludge	82.42	54.95	40.09	4.96	23.25	4.36	3.77	0.69	12.98	10.36

M_t refers to the total moisture; A_d, V_d, and FC_d respectively refer to ash, volatile, and fixed carbon on a dry basis; ultimate analysis was conducted on a dry basis; Q_d refers to the dry-basis calorific value.