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Research Paper

Sewage sludge disruption through sonication to improve the co-preparation of coal–sludge slurry fuel: The effects of sonic frequency

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HIGHLIGHTS

- Sonication with different frequencies is used to disrupt sludge flocs.
- The disrupted sludge is mixed with coal to prepare coal–sludge slurry.
- Effects of sonic frequency on reducing slurry viscosity are studied.
- Low-frequency sonication generates more intense cavitation effects.
- Low-frequency sonication has more obvious effects of reducing slurry viscosity.

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ABSTRACT

The sewage sludge volume has been increasing annually, and if not treated properly, this sludge endangers the environment and human health. Sludge can be considered as a carbon-containing material, and the energy within is utilized easily and economically by blending it with coal to prepare a slurry fuel called coal–sludge slurry (CSS). However, sludge is always disrupted before CSS preparation because of its high bound water content and viscosity. In this study, sonication was performed to disrupt sludge and to enhance co-slurrying with coal. The effects of sonic frequency were highlighted, and the results showed that low-frequency sonication significantly reduces viscosity. Moreover, this process improved CSS slurrying. The characteristic viscosity (the apparent viscosity measured at a shear rate of 100 s^{-1}) of CSS prepared with raw sludge was 1663.6 mPa·s; following sludge disruption via sonication (the specific energy was 30 kJ/g dry sludge) at 15, 25, and 35 kHz, the characteristic viscosities of prepared CSSs decreased to 1121.6, 1194.8, and 1234.3 mPa·s, respectively. On the basis of the dynamic model of a sonic cavitation bubble, low-frequency sonication intensified cavitation such that the radius and impact velocity of a cavitation bubble increased. This finding was consistent with experimental results.

1. Introduction

Sewage sludge is a solid condensate generated via wastewater treatment processes and comprises approximately 0.5%–1% of wastewater volume. In fact, sludge output has increased considerably with the recent increase in wastewater volume. Sludge contains high amounts of salts, heavy metals, pathogens, nutrient substances, and organic pollutants, among others; thus, untreated sludge poses pollution hazards when discharged into the environment [1,2].

China is among the few countries that consider coal to be a primary energy source, and coal consumption in this country reached 3.51 billion tons in 2014. Oil demand also increased continuously as a result of rapid economic development; therefore, the nation's dependency on imported oil increased to 59.5% in 2014. At present, China faces the two serious problems of energy supply and environment pollution. In light of this situation, sludge recycling is of practical significance.

The use of coal–water slurry (CWS) is advantageous in that it clearly protects the environment against storage, transport, and combustion emissions. Thus, this liquid fuel has become an energy-saving, environment-friendly oil substitute in China. The addition of sludge into CWS was proposed recently to produce a sludge-containing slurry fuel called coal–sludge slurry (CSS) [3,4] that is used to fuel power plant boilers, industrial boilers, and furnaces. This slurry fuel is also regarded as a gasification material [5,6].

CSS technology is advantageous over other sludge disposal technologies (landfill, agricultural usage, digestion, and incineration) in the following main ways. First, CSS is cost efficient because complex and expensive sludge pretreatments are unnecessary. Second, the high moisture content in sludge can be transformed into free water

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after proper processing, thus saving on the clean water required for CSS preparation. Third, sludge can be disposed of on a large scale. Finally, the energy in sludge is recycled by burning or gasifying sludge-containing slurry. Given these advantages, CSS technology has become an optimum sludge disposal method [7].

As a result of the complex floc structure of and extracellular polymeric substances in sludge [8–11], coal slurry viscosity typically increases significantly after sludge addition. High viscosity results in high difficulty in stirring and mixing and in the following transportation, spray and combustion for the slurry. Hence, the proportion of sludge blending in CSS is low. Disrupting sludge flocs therefore improves the performance of sludge in slurry preparation.

Sonication treatment [12–14] is a common sludge disruption technique. Sonic cavitation generates powerful hydraulic shear forces accompanied by extremely high local temperature (5000 °C) and pressure (500 bar). Exposing sludge to sonication destroys flocs and microbial cell walls, in addition to releasing the water trapped in these flocs and cells [15–18]. Bougrier et al. [15] disrupted sludge at a sonication energy of 1.35 kJ/g dry sludge (DS). The average particle size decreased from 31.99 μm to 18.50 μm, whereas the ratio of soluble chemical oxygen demand (SCOD) to total chemical oxygen demand increased from 5.8% to 16.1%. Chu and Lee [16] reported that after sonication treatment, the amount of negative charge on sludge particle surfaces increased. Moreover, particle density was enhanced because sonication deconstructed and eliminated irregular and loose sludge flocs.

In the present study, sonication is conducted to disrupt sludge. Subsequently, the pretreated sludge is mixed with coal to prepare CSS, and the co-slurrying performance of sludge and coal is determined. Sound waves have a wide frequency range, and they are classified into infrasonic and ultrasonic waves by the sonic frequency. Specifically, sound wave of less than 20 kHz is taken as infrasonic wave and that of over 20 kHz is taken as ultrasonic wave. Different sonic frequencies have very diverse performances and applications. Infrasonic waves of lower frequency are often used in signal propagating, human organs' activity diagnosing, and military weapons. Ultrasonic waves of higher frequency are often used in accurate surface cleaning, including electronic components, silicon chips, microchips, etc. Sound waves with frequency near 20 kHz are commonly used in cells and tissues breaking, and large molecules degrading. They also apply to the sludge flocs disrupting in the paper. Determining the influences of sonic frequency on sludge disruption and improving co-slurrying performance in practice are important topics. However, research in this field has been scarce.

This study mainly focuses on the following three points: (1) the effects of sonic frequency on sludge disruption in terms of SCOD and sludge particle size; (2) the influences of sonic frequency on the improvement of co-slurrying performance of sludge and coal in terms of the characteristic viscosity (the apparent viscosity measured at a shear rate of 100 s^{-1}, and the detail is shown in Section 2.4.2) and rheological properties of CSS; and (3) the effects of sonic frequency on sonic cavitation based on the dynamic model of a cavitation bubble.

2. Experimental

2.1. Materials

Sludge was collected from a wastewater treatment plant located at Hangzhou City, China, and the sample was stored at 4 °C before use. Bituminous coal was obtained from Pingdingshan, China. Table 1 shows the results of the proximate and ultimate analyses on the test materials. The sludge water content was 82.42%. In Table 1, M_t refers to the total moisture; and A_d, V_d, and FC_d are the ash, volatile, and fixed carbon concentrations on a dry basis, respectively. Ultimate analysis was conducted on dry basis. Q_d refers to the dry-basis higher heating value (HHV).

Chemical additives are important components of CWS/PCS. A suitable additive decreases aggregation forces among particles and increases the surface charge of particles, thus enhancing slurry stability. In CSS preparation, the chemical additive used was a copolymer of methylene naphthalene, sulfonate styrene, and sulfonate maleate. This copolymer exhibited significant dispersion effects, according to a previous work [4].

2.2. Sonication instrument and sludge pretreatment

A sonic cell disruption system (GL-650 SD, Nanjing Xian'ou Instruments Manufacture Co., Ltd., China) was utilized for sonication. Three frequencies (15, 25, and 35 kHz) can be generated by changing the different probes of the sonication generator, these frequencies are commonly used in sludge flocs disrupting; output sonic power was continuously adjusted across the range of 0 W–650 W.

The energy supplied to disintegrate sludge was expressed as a specific energy input (E_{Spec}), which was defined as the energy input per unit mass of dry sludge (DS). E_{Spec} is a function of sonic power, sonic duration, sludge volume, and DS content, as shown in the following equation:

$$E_{Spec} = \frac{P \times t}{V \times DS},$$

where E_{Spec} is the specific energy input (kJ/g DS); P is the sonic power (kW); t is the sonic duration (s); V is the sludge volume (L); and DS is the dry–solid content (g/L).

For each experiment, 100 mL of sludge samples (5% solid concentration) was obtained. Output sonic power was set at 325 W while the sonic frequencies were set to 15, 25, and 35 kHz. The sludge samples were treated with two E_{Spec} inputs, that is, 4 and 30 kJ/g DS. The temperature of the samples was controlled at 20 °C using a constant temperature circulator (DHX-5, Nanjing Xian'ou Instruments Manufacture Co., Ltd., China).

2.3. Measurement of the physicochemical properties of sludge

2.3.1. Soluble organic matters in sludge

Soluble organic matters are substances that are dissolved in an aqueous phase supernatant. Prior to measurement, particulate sludge

Table 1
Proximate and ultimate analysis results of the tested coal and sludge.

Sample	Proximate analysis (%)				Ultimate analysis (%)					Q_d (MJ/kg)
	M_t	A_d	V_d	FC_d	C_d	H_d	N_d	$S_{t,d}$	O_d	
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; and A_d, V_d, and FC_d are the ash, volatile, and fixed carbon concentrations on a dry basis, respectively. Ultimate analysis was conducted on dry basis. Q_d refers to the dry-basis higher heating value (HHV).