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Numerical and experimental evaluation of continuous ultrasonic sludge treatment system

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Ultrasonic disintegration is a very promising sludge pretreatment method that leverages the cavitation effect to produce extreme physical environments characterized by high temperatures and high pressures. This process disintegrates sludge structure features, promotes sludge dewatering, and aides resource recovery. This paper presents a newly designed continuous ultrasonic sludge treatment device. The characteristics of the ultrasonic wave propagated in the activated sludge were simulated, with the results showing that at lower frequencies, the acoustic pressure energy distribution exhibits more local concentrations, whereas at 80 kHz, the energy distribution is relatively uniform as a result of the interference of standing waves. Subsequently, activated sludge was ultrasonically treated with different exposure times and frequencies. The sludge's capillary suction time, particle size, and moisture content were measured. The results showed different trends for each of the investigated parameters. The dewatering performance was best when the exposure time was 5–10 s. Finally, different substances were added to the ultrasonically treated sludge to analyze the effects of ultrasonic treatment on anaerobic digestion. The gas production rate was higher when glucose was the added substance than it was for yeast. The highest total concentration of produced gas, including both hydrogen and methane, was 34% for an ultrasonic input power of 200 W at a 25 kHz frequency, an exposure time of 20 s, and with 30 g of added glucose. The gas production rate was found to be higher at the lower frequency when frequency was the only variable. These experiments demonstrate that ultrasonic treatment can change the structure of sludge particles and the moisture content of the sludge, improving sludge dewatering performance. Furthermore, after ultrasonic treatment can improve gas production.

1. Introduction

With industrial development and the growth of urban populations, urban sewage emissions have been increasing, as has the sewage treatment by-product, sludge. Sludge consists of organic matter, heavy metals, and pathogenic bacteria, in addition to a significant amount of water. Its physical and chemical properties are not very stable, changing significantly during storage, transportation, and processing; when improperly disposed of, sludge causes serious harm to the environment [1–5]. Wastewater treatment plants utilize physical, chemical, and biological processes to treat wastewater and remove contaminants. The treatment and disposal of excess sludge accounts for approximately 60% of the total operating cost; in addition, greenhouse gases from the wastewater sector have increased [6–8]. Incineration, ocean discharge, land application, and composting are the common sludge disposal methods used over the years; these methods are no longer reliable because of economic constraints and environmental concerns [9]. Therefore, advanced sludge treatment technology has gained the attention of researchers around the world [10].

Ultrasonic pretreatment is well-known to be one of the most powerful sludge disintegration methods, developed in the 1990s to decompose microbial cells to extract intracellular organic matters [11]. Ultrasonic pretreatment produces a rapid succession of extreme conditions: local high temperature and high pressure in the water, rapid discharge of microbubbles, ultra-high speed jets, and others [12–16]. These extreme conditions disintegrate the flocs structure and cell walls of biological sludge components, releasing organic matter [17]. This process can completely hydrolyze the sludge in a very short period of time, significantly shortening the overall sludge digestion time. However, the disintegration of the sludge flocs structure and cells releases water trapped in the cells that is difficult to remove from the sludge. Therefore, improving the dewatering performance of the disintegration process would reduce the sludge volume.

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To date, ultrasonic sludge pretreatment has been researched extensively at China and abroad. In 2006, Bougrier [18] studied the effects of ultrasonics, ozonation, and thermal pretreatment on waste-activated sludge, with the objective of enhancing the efficiency of anaerobic digestion. The best results were obtained by applying ultrasounds with an energy of 6250 or 9350 kJ/kg TS and a thermal treatment at 170 or 190 °C. In 2007, Shen [19] investigated the ultrasonic dewatering and disintegration of residual activated sludge under static and dynamic conditions: under static conditions, sludge dewatering should be performed at low power and for a short time, with the highest dewatering rate nearly 16% greater compared with non-ultrasonic treatment; under dynamic conditions, the total dewatering rate nearly 23% greater compared with non-ultrasonic treatment at low power (50 W). Erden [20] researched the disintegration of biological sludge by ozone oxidation and ultrasonic treatment. In terms of sludge stabilization, the highest reduction of volatile solids and protein degradation were obtained with ultrasonic treatment. In 2011, Guo [21] studied low frequency ultrasonic treatment in both batched and continuous operations with the goal of enhancing hydrogen production by bacteria: optimal ultrasonic conditions were obtained at an ultrasonic exposure time of 10 s and intensity of 100 W in batch experiments resulting in an increase in hydrogen production of 20%. In 2012, Gallipoli [22] applied ultrasound at 200 kHz to treat sewage sludge with the goal of obtaining efficient sludge disintegration and the removal of the linear alkyl benzene sulphonates at the same time. This high-frequency ultrasound irradiation was also found to be effective in terms of floc disintegration and soluble organic matter release, in particular for energy inputs higher than 30,000 kJ/kg TS. In 2013, Yeneneh [23] found that combined ultrasonic and microwave exposure produced more favorable effects on sludge than either method alone, increasing the amount of hydrogen production. Ruiz-Hernando [24] found that the application of ultrasonic waves to the sludge significantly reduced its viscosity, thixotropy, and mean particle size, while its capillary suction time was increased. Nevertheless, ultrasonication treatment improved the dewatering process by increasing the total solid content of the sludge after centrifugation. In 2014, Tyagi [25] investigated the effects of alkali-enhanced microwave (MW) (50–175 °C) and ultrasonic (US) (0.75 W/mL, 15–60 min) pretreatments, on solubilization and the subsequent anaerobic digestion efficiency of pulp and paper mill waste-activated sludge. Significantly higher sludge solubilization was observed for alkali-assisted MW and US pretreatment methods than individual MW and US pretreatments. Batch anaerobic digestion experiments revealed that the highest biogas generation was observed for combined US-alkali (pH 12,60 min) pretreatment method. An ultrasound and a microwave pretreatment were compared in a long-term digestion experiment [26], and the effect of ultrasonic pretreatment was greater than that of microwave pretreatment. In 2015, Liu [27] investigated the effect of extracellular polymeric substances (EPS) disintegration on anaerobic fermentation of waste-activated sludge. The experimental results showed that more organic substances were released from sludge with increased ultrasonic density, and the EPS were completely disintegrated at ultrasonic exposures greater than 2.0 W/mL and 15 min. In Yeneneh's [28] study, a combination of microwave pretreatment with ultrasonic pretreatment was compared to microwave only pretreatment. The enhanced performance obtained in combined microwave–ultrasonic pretreatment over individual pretreatment options for enhanced sludge solubilization and biogas production make this process very promising for future industrial scale sludge pretreatment applications in wastewater treatment plants. In 2016, Zielewicz [29] studied the disintegration of various sludges in ultrasonic disintegrators of varying heads and emitter structures at the same energy density. The effects of ultrasonic disintegration strongly depend on the type of disintegrator and sonication time, and sludge concentration was more susceptible to ultrasonic disintegration. Kavitha [30] investigated the influence of ultrasonic-aided bacterial disintegration on the aerobic degradability of sludge. Results showed that the effect of ultrasonic-aided bacterial disintegration was better than ultrasonic or bacterial disintegration treatments alone.

Ultrasonic sludge disintegration is a research subject with broad prospective applications; however, because ultrasonic sludge treatment has been tested under predominantly static conditions, the method has been difficult to apply in practice. Therefore, this study will further the practical application of ultrasonic sludge pretreatment through the design and development of a new continuous ultrasonic generator, in which the import and export of sludge is continuous, and the ultrasonic treatment is batched.

2. Methods

2.1. Overview

The residual sludge from a sewage treatment plant was ultrasonically pretreated with different ultrasonic exposure times and frequencies. The dewatering performance and anaerobic digestion were evaluated based on the parameters of moisture content and capillary suction time (CST), and the optimum ultrasonic conditions were obtained.

Sewage treatment follows the inverted A^2O (Anaerobic–Anoxic–Oxic) process. When the supernatant is removed after standing for 24 h, the water content of the sludge is 99.69%. The continuous ultrasonic sludge treatment system applied input power of 0–400 W at a frequency of 0–45 kHz to a processing capacity of 2 L. A YN-LDE sludge pipe flow meter with a flow of 0–0.5 L/s was used to move sludge into the treatment tank. The suction filtration method was used to dehydrate the sludge after pretreatment at a suction pressure of 70 kPa. Moisture content was measured with an MA150 infrared moisture analyzer, and CST was measured with a Triton Electronics Type 319 Multi-CST analyzer. The particle size was measured with a Beckman Kurt Multisizer 3 particle count and particle size analyzer. The hydrogen content in the gas was measured with 3420A gas chromatography, using a thermal conductivity detector with a 5A molecular sieve and a $3\,m \times 3\,mm$ chromatographic column.

2.2. Equipment

According to the previous research outlined in the Introduction, we designed a continuous ultrasonic sludge treatment system as shown in Figs. 1 and 2, consisting of three primary components: a frequency generator, an ultrasonic transducer, and a treatment tank. A flow meter and metering pumps were auxiliary equipment. In this design, we chose a YN-LDE sludge pipe flow meter and a DP-130 high pressure diaphragm pump. The frequency generator converts alternating current (AC) power to an oscillating signal with an ultrasonic frequency. This signal is then supplied to the ultrasonic transducer, which converts the power of the ultrasonic signal into mechanical energy in the form of an ultrasonic vibration. The tank contains the sludge during treatment.

The ultrasonic transducers are the core components of the ultrasonic sludge treatment device, converting the power of the ultrasonic signal from the frequency generator into mechanical energy in the form of ultrasonic vibrations to achieve sludge disintegration. The transducers used in this design were horn-type sandwich piezoelectric ceramic transducers made of PZT-4 emission-type piezoelectric ceramic material with resonant frequencies of 25, 45, and 68 kHz, input powers of 40 W and 80 W, and power capacities of 2–3 $W/(cm^3/kHz)$. There are two methods