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Enhancement of ultrasonic disintegration of sewage sludge by aeration

He Zhao¹, Panyue Zhang², Guangming Zhang^{1,*}, Rong Cheng¹

1. School of Environment and Natural Resource, Renmin University of China, Beijing 100872, China. E-mail: zhaoh628@163.com
 2. College of Environmental Science and Engineering, Beijing Forestry University, Beijing 100083, China

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ABSTRACT

Sonication is an effective way for sludge disintegration, which can significantly improve the efficiency of anaerobic digestion to reduce and recycle use of sludge. But high energy consumption limits the wide application of sonication. In order to improve ultrasonic sludge disintegration efficiency and reduce energy consumption, aeration was introduced. Results showed that sludge disintegration efficiency was improved significantly by combining aeration with ultrasound. The aeration flow rate, gas bubble size, ultrasonic density and aeration timing had impacts on sludge disintegration efficiency. Aeration that used in later stage of ultrasonic irradiation with low aeration flow rate, small gas bubbles significantly improved ultrasonic disintegration sludge efficiency. At the optimal conditions of 0.4 W/mL ultrasonic irradiation density, 30 mL/min of aeration flow rate, 5 min of aeration in later stage and small gas bubbles, ultrasonic sludge disintegration efficiency was increased by 45% and one third of ultrasonic energy was saved. This approach will greatly benefit the application of ultrasonic sludge disintegration and strongly promote the treatment and recycle of wastewater sludge.

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Introduction

Waste activated sludge produced by wastewater treatment process is continuously increasing and causes various pollution problems (Samolad and Zabaniotou, 2014). To prevent environmental pollution of sludge, many processes were developed. Sludge anaerobic digestion is a cost-effective and energy-saving process that can convert organic pollutants in sludge to biogas. To achieve high anaerobic digestion efficiency, sludge should be disintegrated to release the inner substances (Le et al., 2013b).

Sonication is very efficient for sludge disintegration and has attracted many attentions (Wang et al., 1999; Li et al., 2009). Under ultrasonic irradiation, “hot spots” with high temperature and pressure (5000 K, 1000 atm) pyrolyze sludge,

strong shear forces mechanically attack sludge flocs, and hydroxyl free radical (redox potential 2.80 eV) may oxidize sludge (Kang et al., 2006; Koda et al., 2011). Among these mechanisms, hydro-mechanical force is the predominant one for sludge disintegration (Wang et al., 2005). Due to high energy consumption of ultrasonic sludge disintegration, many techniques, including thermal, alkaline, ozone, and acid, were used to improve the ultrasonic efficiency and reduce the energy (Wett et al., 2010; Kim et al., 2010; Liu et al., 2008; Xu et al., 2010). But these methods have disadvantages of high reagent cost and secondary pollution. Aeration is low cost and non-pollution, and thus is a potential method to improve ultrasonic sludge disintegration.

Gas bubbles in the ultrasonic system can act as nucleuses of cavitation bubbles (Eller, 1969). Through aeration, more

* Corresponding author. E-mail: zgm@ruc.edu.cn (Guangming Zhang).

cavitation bubbles were formed. The cavitation effects were then strengthened. Thus ultrasonic sludge disintegration may be enhanced by aeration. As our best knowledge, aeration has not been used to enhance the ultrasonic sludge disintegration.

In this article, the feasibility of aeration to enhance the ultrasonic sludge disintegration was tested. Conditions of aeration were optimized. Energy consumption of aeration-sonication sludge disintegration was analyzed. The aim was to develop an aeration-sonication sludge disintegration method to improve the efficiency and reduce the energy consumption.

1. Materials and methods

Sludge was collected from a local wastewater treatment plant that used A/O process. The sludge had a total solid content (TS) of 1.3%–1.5% and a volatile solid content (VS) of 0.8%–1.1%. The initial soluble chemical oxygen demand (SCOD) was 62–83 mg/L. The pH value was 6.5–8.5.

Aeration was conducted with a LP-20 diaphragm blower (Resun Co. Ltd., China). Aeration flow rate was controlled by a flow meter. Gas bubble size was controlled by aerators with three different pore sizes of 80–100, 180–200 and 250–280 μm . Ultrasonic irradiation was performed with a JY92-II ultrasonic generator (NingboXinzh Technology Co., China) with an ultrasound frequency of 24 kHz. Each time 250 mL of sludge was tested. The ultrasonic irradiation time was 15 min, which was determined by the preliminary experiments. Temperature of the sludge was controlled below 30 °C with a circulating cooling water system (ST22RC/B-E3000, Hengxing Co., China).

All analyses were performed according to APHA standard methods (APHA, 1995). All experiments were repeated two or three times and the average results were reported. Error bars in the figures refer to the standard deviation of results from repetitive experiments. T-test was used to analyze the significance of the data and all results met the requirement ($\alpha = 0.05$).

2. Results and discussion

In this study, sludge disintegration efficiency was investigated through the determination of soluble chemical oxygen demand (SCOD). The higher the SCOD was, the higher the sludge disintegration efficiency was (Yu et al., 2013). The results are shown in Fig. 1 (inset). The SCOD was increased by 40% from 519 to 711 mg/L at aeration flow rate of 50 mL/min, showing significant enhancement of sludge disintegration by aeration.

In order to obtain the best efficiency of aeration on ultrasonic sludge disintegration, different operation parameters including aeration flow rate, gas bubble size, ultrasonic density and aeration timing were investigated.

2.1. Impact of aeration flow rates on ultrasonic sludge disintegration

Effects of aeration flow rates on ultrasonic sludge disintegration were studied, and the results are shown in Fig. 1. At

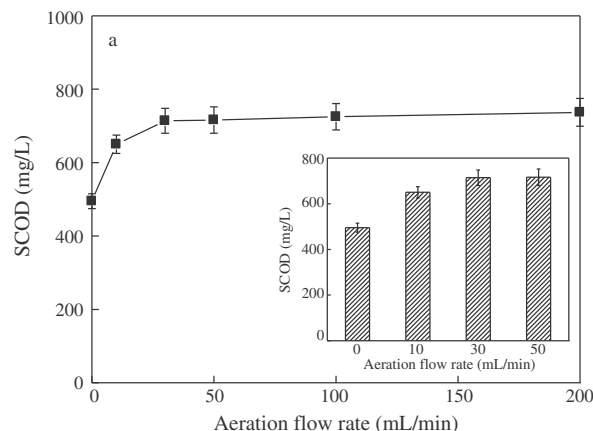


Fig. 1 – Effects of aeration flow rate on ultrasonic sludge disintegration efficiency (15 min aeration time, 0.5 W/mL ultrasonic density, middle size bubble size).

relative low aeration flow rate (below 30 mL/min), sludge disintegration efficiency was increased obviously. When the flow rate was above 50 mL/min, little increase of sludge disintegration efficiency was observed. Considering the efficiency and energy cost, aeration flow rate of 30 mL/min was the optimal to enhance the ultrasonic sludge disintegration.

At aeration flow rates below 30 mL/min, large quantities of gas bubbles were introduced into the sludge. Gas bubbles provided more nucleuses of cavitation bubbles and then enhanced the cavitation effects, which led to stronger shear forces. So, ultrasonic sludge disintegration was efficiently improved by higher aeration flow rate. At aeration flow rate above 50 mL/min, more gas bubbles were introduced into the sludge. Due to high concentration of gas, surface tension of the liquid became lower (Lubetkin, 2003). The lower surface tension would decrease the strength for cavitation bubble growth, then the intensity of cavitation effects decreased because of the weaker bubble growth (Brennen, 1995; Jarman, 1959). So, ultrasonic sludge disintegration was hindered by too high aeration flow rate.

2.2. Impact of gas bubble size on ultrasonic sludge disintegration

The induced gas bubbles act as nucleus for cavitation, but cavitation bubbles have fixed resonance size at given ultrasonic frequency (Thompson and Doraiswamy, 1999), so gas bubbles of different sizes might work differently. Small, medium and big gas bubbles which were generated by aerators with pore size of 100–120, 180–200 and 260–280 μm were investigated. Bubbles were generated from the aerator, entered the sludge, aggregated during the movement and were disrupted by ultrasonic waves, so the size of bubbles kept changing. But bubbles from larger pores kept larger than those from smaller pores. Results are shown in Fig. 2. The SCOD of the treated sludge increased from 548 to 779, 722, 636 mg/L respectively, showing a 43.4%, 33.6% and 17.6% improvement with small, medium and big size gas bubbles, respectively. Please note that real waste activated sludge was used. The sludge was different each time and thus the control sample gave different values each time.

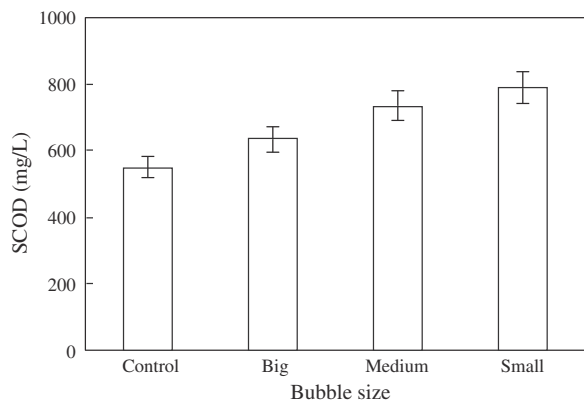


Fig. 2 – Effects of gas bubble size on ultrasonic sludge disintegration efficiency (30 mL/min flow rate, 15 min aeration time, 0.5 W/mL ultrasonic density).

Small bubbles were the most efficient to assist the ultrasonic sludge disintegration. Because the size of small bubbles was close to the resonance size that was 136 μm at 24 kHz ultrasonic frequency (Zhao et al., 2014), small bubbles could act as nucleus much more easily. So cavitation effects were stronger than those with medium or big size gas bubbles, leading to better ultrasonic sludge disintegration. Besides, small gas bubbles could disperse sludge flocs, which was beneficial to the sludge disintegration. So, the SCOD was increased significantly by aeration with small bubbles.

2.3. Effects of aeration on sludge disintegration under different ultrasonic intensities

Under ultrasonic irradiation densities from 0.1 to 1.2 W/mL, effects of aeration on ultrasonic sludge disintegration were investigated, and the results are shown in Fig. 3. As observed, SCOD with aeration was basically higher than that without aeration. Aeration was the most effective under ultrasonic irradiation density of 0.4 W/mL; the SCOD increased from 448 to 712 mg/L, showing a 58.9% increase.

Obviously, the sludge disintegration efficiency was poor under low ultrasonic irradiation densities (<0.3 W/mL). Since formation of evident cavitation effects should meet energy

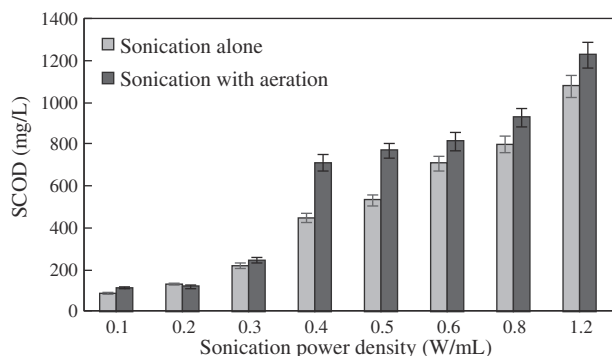


Fig. 3 – Effects of ultrasonic density on ultrasonic sludge disintegration efficiency (30 mL/min flow rate, 15 min aeration time, small size bubbles).

threshold, cavitation effect was weak under low ultrasonic irradiation density. Limited nucleuses were needed by weak cavitation effects. Therefore, even with more gas bubbles introduced by aeration, no obvious improvement of disintegration efficiency was observed at low ultrasonic densities. Once the ultrasonic irradiation density was above 0.8 W/mL, gas bubbles might be collapsed by strong shock waves generated by the ultrasonic irradiation. Thus the gas bubbles provided by aeration could be not utilized. As a result, the sludge disintegration efficiency could not be effectively improved by aeration under high density ultrasonic irradiation.

2.4. Impact of aeration timing on ultrasonic sludge disintegration

Since ultrasound can degas the sludge (Eskin, 1995), the gas concentration was different at different stages of ultrasonic irradiation process. Aeration in different stages might have different effects on the sludge disintegration. Aeration operated in three stages (early 5 min, middle 5 min and later 5 min) of ultrasonic irradiation was then investigated, and the results are shown in Fig. 4. The SCOD was increased by 23%, 35%, 45% and 60% by the early, middle, later stage and whole period aeration, respectively (from 466 to 572, 629, 678, and 728 mg/L respectively). Efficiency of 5 min aeration in the later stage was close to that with 15 min aeration in whole period. But 66.7% of aeration energy was saved since only 5 min aeration was needed. Therefore, aeration in the later stage was the most effective.

Without aeration, gas concentration in the sludge decreased with longer ultrasonic time because of the degassing ability of ultrasonic irradiation. With lower gas concentration, cavitation effects decreased, leading to weaker shear forces. So, ultrasonic disintegration efficiency was the worst at the later stage.

With aeration in early stage, gas in the sludge was surplus for cavitation effect formation. So gas bubbles introduced by aeration were wasted. With aeration in the middle and later stages, gas bubbles were used to generate cavitation bubbles. Especially in the later stage, gas bubbles were fully utilized, leading to strong shear force. Therefore, aeration used in the later stage was the most effective.

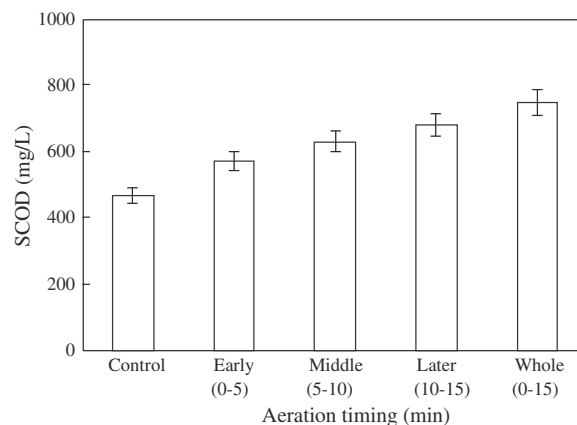


Fig. 4 – Effects of aeration timing on ultrasonic sludge disintegration efficiency (30 mL/min flow rate; 0.4 W/mL⁻¹ ultrasonic density, small size bubbles).

Table 1 – Effects of different assisting methods on ultrasonic disintegration of sludge.

Assisted method	Conditions	Increase of ultrasonic disintegration efficiency	References
Alkaline	pH = 12	30%	Kim et al., 2010
Alkaline and high pressure	900 mg NaOH/L, 83 MPa	26%	Sahaa et al., 2011
Ozone	1 g/hr	18%	Xu et al., 2010
High pressure and thermal	2 bar, 75 °C	10%	Le et al., 2013a
Thermal	80 °C	12.5%	Sahinkaya and Sevimli, 2013

In summary, aeration improved ultrasonic sludge disintegration effectively. Assisted by 5 min aeration with small bubbles, the disintegration efficiency was increased by 45% from 466 to 678 mg/L under 0.4 W/mL of ultrasonic irradiation. In comparison with other methods listed in Table 1, aeration showed great advantages of high efficiency in enhancing the ultrasonic sludge disintegration with no reagent consumption.

Furthermore, aeration was also energy saving. Under 0.4 W/mL of ultrasonic irradiation for 15 min assisted by 5 min aeration, SCOD was increased to 678 mg/L (Fig. 4), which was similar with that under 0.6 W/mL of ultrasonic irradiation for 15 min alone (709 mg/L, Fig. 3). Therefore, 1/3 of ultrasonic power consumption was saved. On the other hand, 0.6 L air was needed to treat 1.0 L sludge (30 mL/min × 5 min for 250 mL sludge). With a typical blower (L9.5-120/49-LB, Sunsun Co. Ltd., China), which has an operation power of 1100 W and a flow rate of 0.98 m³/min, 1.12 × 10⁻⁵ kWh was needed to provide 0.6 L air, which was negligible. Therefore, one third of ultrasonic energy was saved by aeration.

At present, wastewater treatment accounts for 1%–2% of energy consumption in some countries like USA, China, and Germany. In the process of wastewater treatment, sludge is a major problem. Anaerobic digestion can utilize sludge and help balance the energy consumption of wastewater treatment plants. Ultrasonic sludge disintegration has been used to improve the anaerobic digestion efficiency in practice. But the energy consumption of ultrasonic irradiation is high. Assisted by aeration, the ultrasonic sludge disintegration is greatly improved with little energy, which is beneficial to increase the anaerobic digestion efficiency. Thus, significant energy reduction can be realized in WWTPs wastewater treatment plants, which will promote the development of wastewater treatment and reduce the energy consumption as a whole.

3. Conclusions

Aeration was a simple, effective, and cost efficient way to improve the ultrasonic sludge disintegration. Small gas bubbles were more effective than middle and big gas bubbles; aeration worked the best at ultrasonic power density of 0.4 W/mL; and aeration in the later stage of ultrasonic irradiation was more effective than in the early or middle stage. Assisted by 5 min aeration in the later stage with flow rate of 30 mL/min, the sludge disintegration efficiency was increased by 45% under 0.4 W/mL of ultrasonic irradiation. One third of ultrasonic energy might be saved through aeration. Effective

and energy-saving aeration-sonication sludge disintegration would promote the development of sludge treatment and utilization.

Acknowledgments

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