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Short communication

Ultrasonic reduction of excess sludge from the activated sludge system

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Abstract

Sludge treatment has long become the most challenging problem in wastewater treatment plants. Previous studies showed that ozone or chlorine effectively liquefies sludge into substrates for bio-degradation in the aeration tank, and thus reduces the excess sludge. This paper employs ultrasound to reduce the excess sludge from the sequential batch reactor (SBR) system. Partial sludge was disintegrated into dissolved substrates by ultrasound in an external sono-tank and was then returned to the SBR for bio-degradation. The results showed that ultrasound (25 kHz) effectively liquefied the sludge. The most effective conditions for sludge reduction were as following: sludge sonication ratio of 3/14, ultrasound intensity of 120 kW/kgDS, and sonication duration of 15 min. The amount of excess sludge was reduced by 91.1% to 17.8 mg/(L d); the organic content and settleability of sludge in the SBR were not impacted. The chemical oxygen demand (COD) removal efficiency was 81.1%, the total nitrogen (TN) removal efficiency was 17–66%, and high phosphorus concentration in the effluent was observed.

Keywords: Ultrasound; Sludge minimization; Intensity; SBR; Effluent quality

1. Introduction

Biological treatment is the most important technology in wastewater purification in which large amount of excess sludge is generated. The cost of sludge treatment accounts for 30–60% of the operational cost of the whole wastewater treatment plant [1] and presents high technical challenge. The best countermeasure is to eliminate the excess sludge from the aeration process. Previous researches show that ozone and chlorine gases can effectively dissolve the excess sludge, which is then recycled into the aeration tank as substances for microorganisms, thereby leads to 60–100% reduction of excess sludge within the process [2–6]. However, ozonation is a very costly process, and chlorination causes the concern of chlorinated by-products and chlorine gas itself imposes risks to the activated sludge system. Effective physical disintegration of sludge can decrease the disadvantages of chemical oxidations. Researches have shown that sonication is a very effective method to liquefy sludge [7–12] by disrupting the sludge floc, lysing the cells, and releasing the cell materials and extra-cellular polymer substrates (EPS) into water. Powerful ultrasound causes acoustic cavitation in liquids in which millions of small bubbles collapse to produce very high temperature (5000 K), pressure (500 bar), and extreme shear forces that mechanically attack sludge flocs [13]. Sonication also generates OH radical, which reacts with the EPS and thus improves the sludge dewater ability [10] and may enhance the sludge biodegradability. The paper used ultrasound to treat partial sludge and then recycled the disintegrated sludge into the bioreactor as substances for degradation. A typical activated sludge system, sequential biological reactor (SBR), was used for this study. The purpose of this study was to find a new method to safely and efficiently minimize the excess sludge.

2. Materials and methods

The seed sludge was collected from secondary sedimentation tanks in a wastewater treatment plant and was stored at 4 °C before use. The sludge had water content of 99%, pH of 7.23, suspended solids concentration (SS) of 9234 mg/L and volatile solids concentration (VS) of 7580 mg/L. The wastewater used in the experiments was artificial wastewater with

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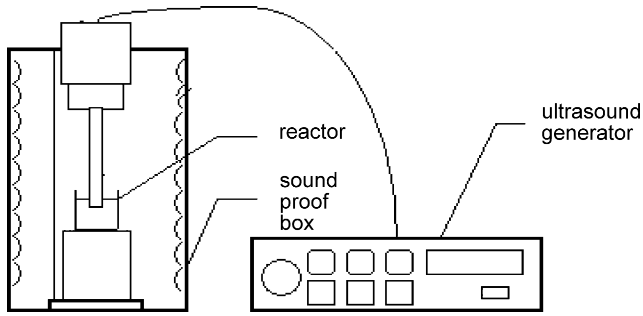

Fig. 1. Schematic sonication system.

400 mg/L glucose, 120 mg/L protein pepton, 150 mg/L NH_4Cl, 35 mg/L KH_2PO_4, 10 mg/L $MgSO_4$, 50 mg/L $CaCl_2$, 15 mg/L $FeSO_4{\cdot}7H_2O$, and 100 mg/L $NaHCO_3$. The wastewater had a chemical oxygen demand (COD) of 446 mg/L, total nitrogen (TN) of 23.6 mg/L, and total phosphorous (TP) of 4.6 mg/L. All chemicals were purchased from Ameta (China) and used without further purification.

The sludge sonication was performed in a JY90-II system (Xinzhi, see Fig. 1) that emitted 25 kHz ultrasound waves through a tip with a surface area of 2.12 cm^2. The sound frequency of 25 kHz was selected because sludge disruption is most effective at low frequencies [9,11]. The ultrasonic field was measured with a CS-3 hydrophone (Acoustic Academy of China) and a TDS 3000 oscillograph (Tektronix Inc.). The sono-tank was water-bathed to maintain the temperature in the tank at $20 \pm 2\,°C$. The sludge pH was not adjusted.

Three identical SBRs were operated. Each SBR had a working volume of 7 L, and the airflow rate was 40 L/h to maintain a dissolved oxygen level of 5 mg/L during aeration. The operational cycle of SBR was 6 h, in which 4 h was for aeration and 1 h was for sludge settling. The temperature in the SBRs was maintained $20 \pm 2\,°C$ using water baths and the pH was not adjusted. The SBRs were automatically controlled. One SBR was used as the reference. Each day certain amount of sludge was removed from SBR for sonication and then returned to the SBR. In order to reduce the volume of sludge to be treated, sonication samples were taken by the end of the settling period.

The sludge settlability was evaluated by the sludge volume index (SVI), which is defined as the sludge volume per gram of dry solid (DS) after 30 min sedimentation and is about 70–100 ml/gDS for municipal wastewater sludge. The pH was monitored with a Hach Accurate pH meter. All other parameters were measured following the standard methods [14] Fig. 2.

The sludge concentration in the SBR (MLSS), sludge SVI, and the effluent TN, TP, turbidity and COD were measured for each operational cycle (6 h). The volatile suspended solids (VS) was measured everyday. The soluble chemical oxygen demand (SCOD) of the sonicated sludge was monitored when necessary. Excess sludge was discharged periodically to maintain the MLSS in SBR around 2000 mg/L.

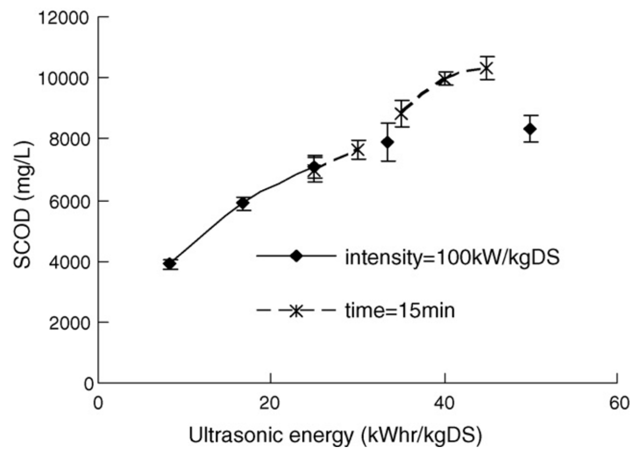

Fig. 2. Increase of sludge SCOD by ultrasonic irradiation, 25 kHz.

3. Results and discussion

3.1. SBRs start-up

The SBRs reached steady operation after 1 month of culturing; the effluent COD was 60–90 mg/L, TN was below 15 mg/L, and TP was 1.5–2.8 mg/L. The MLSS was around 2000 mg/L and the generation rate of excess sludge was around 200 mg/(L d), thus the sludge retention time (SRT) was 10 days. After culturing, column A was used for reference without sonication and columns B and C were used for sonication tests.

3.2. Ultrasonic liquefaction of sludge

The SCOD value was used to evaluate the efficiency of sludge disintegration. Series experimental runs were done to find the optimal sonication conditions for sludge liquefaction and the results were summarized in Fig. 1. Clearly the sonication time was more important than the ultrasonic intensity in determining the sludge disruption degree. The original sludge SCOD was 692 mg/L. The results showed that when the sound intensity was 100 kW/kgDS the SCOD increased almost linearly with the sonication time till 20 min, beyond which time increase had little impact on SCO. Similarly, when the sonication time was 15 min the SCOD increased with the intensity till 160 kW/kgDS and further increase of intensity could not improve the sludge liquefaction. Therefore, following experiments were performed using sonication conditions of 100–160 kW/kgDS and 5–20 min.

3.3. Determination of sludge sonication ratio

The amount of sludge to be sonicated determines the sonication energy, the volume of sono-tank, and the energy to pump sludge between the SBR and sono-tank. Lower ratio means lower energy and less space, but lower ratio is less effective in sludge reduction. On the other hand, higher sludge treatment ratio demands more energy and may deactivate too many microorganisms to maintain the SBR performance.

Initial screening was performed with the sludge sonication ratio of 1/7, 2/7, 3/7, 4/7 and 5/7. The sonication conditions were

160 kW/kgDS and 15 min. For each sludge sonication ratio, the experiment lasted 1 week. Results showed that when more than 2/7 of sludge was sonicated the SBR failed, the sludge floated and did not settle well, and the effluent COD was high (up to 400 mg/L).

The second step was to set the sludge sonication ratio to 1/14, 2/14, 3/14, and 4/14, and the experimental runs lasted 1 month for each ratio. The sonication conditions were 160 kW/kgDS and 15 min. The excess sludge generation rate fluctuated from day to day, and the average value was 154 mg/(L d), 104 mg/(L d), and 3 mg/(L d) when the sludge sonication ratio was 1/14, 2/14, and 3/14, respectively. When the sludge sonication ratio was 3/14 the excess sludge was almost eliminated. When the sludge sonication ratio was 4/14 the reactor was very unstable; the MLSS concentration decreased, and the effluent quality deteriorated significantly. After 30 days, the MLSS concentration in the SBR decreased to 616 mg/L. Therefore, the sludge sonication ratio of 4/14 was improper for SBR operation.

The sludge sonication ratio of 3/14 was preferred since minimum excess sludge was achieved. Different sonication conditions were examined to improve the SBR performance. The sludge generation rate, SVI, and effluent quality were monitored.

3.4. Impact of ultrasound intensity

The ultrasound power densities of 100 kW/kgDS, 120 kW/kgDS, and 140 kW/kgDS were tested, and for each intensity level the experimental runs lasted 1 month. The results showed that the average excess sludge generation rate was 102.6 mg/(L d), 17.8 mg/(L d), and 2.63 mg/(L d) when the sound density was 100 kW/kgDS, 120 kW/kgDS, and 140 kW/kgDS, respectively. The intensity of 140 kW/kgDS seemed to be equally efficient as the intensity of 160 kW/kgDS in sludge reduction. However, the SVI of sludge in the SBR increased quickly to more than 200 mL/gDS when the intensity was 140 kW/kgDS (Fig. 3). The sludge did not settle well and the effluent turbidity reached 19 NTU. The high effluent turbidity indicated that some sludge left the SBR as part of the effluent turbidity, thus the real excess sludge generation rate at intensity of 140 kW/kgDS should be much higher than the observed value of 2.63 mg/(L d). The high sludge SVI and high effluent turbidity showed that intensity of 140 kW/kgDS could not be used for the process.

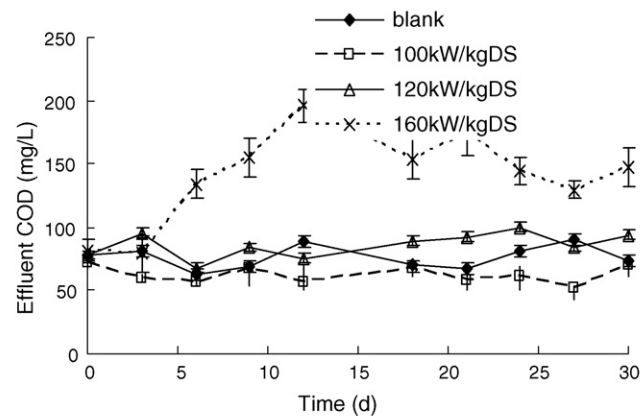

Fig. 4. Effluent COD, 3/14 sludge sonicated, 15 min, 25 kHz.

The sludge SVI for all sonicated systems was slightly higher than that of the blank SBR. Ultrasound waves increased the transport capacity of the bacterial cell and more extra-cellular polymer substances (EPS) attached to the cell surface. High EPS content meant that sludge was difficult to settle down. Shaking by sound waves further decreased the compactness of the EPS. These effects increased the sludge SVI and the impact might last for few hours.

The effluent quality was reported in Figs. 4–6. The average COD of the blank SBR was 74.4 mg/L. The 160 kW/kgDS ultrasound treatment gave high effluent COD and the average COD was 140 mg/L. The 120 kW/kgDS ultrasound treatment gave stable effluent COD in the range of 68–104 mg/L with an average of 84.2 mg/L. The 100 kW/kgDS ultrasound treatment also had low effluent COD. The intensity of 120 kW/kgDS was better than 160 kW/kgDS and 100 kW/kgDS in terms of effluent TN and TP. The effluent TP was quite high when the ultrasound intensity was 160 kW/kgDS. Long-term experiments (6 months) showed that the effluent TN stabilized around 13 mg/L after 3 months (data not included).

When the sonication intensity was 100 kW/kgDS, the effluent turbidity was low (around 5 NTU) in the first 7 days and

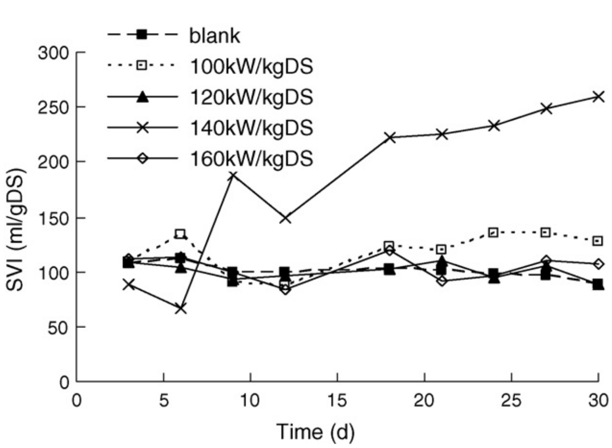

Fig. 3. Sludge SVI change, 3/14 sludge sonicated, 15 min, 25 kHz.

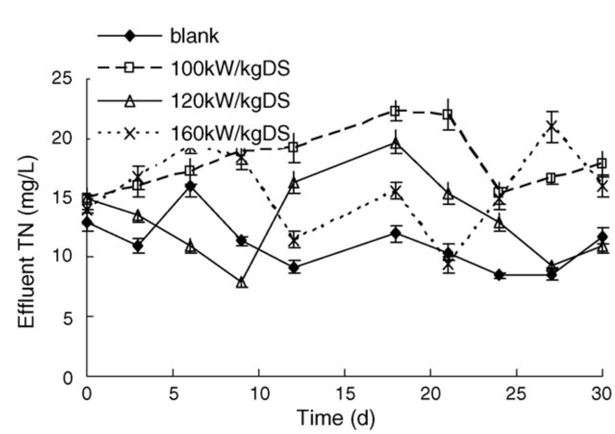

Fig. 5. Effluent TN, 3/14 sludge sonicated, 15 min, 25 kHz.

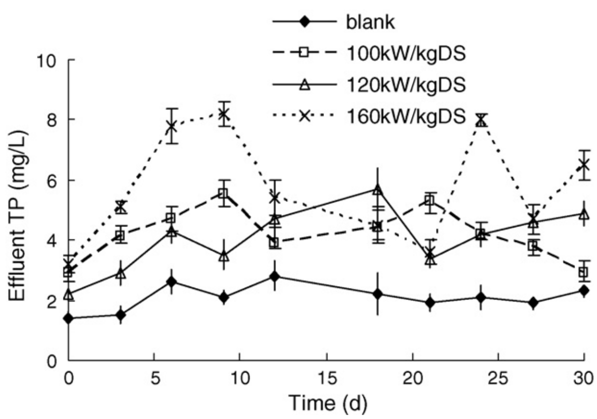

Fig. 6. Effluent TP, 3/14 sludge sonicated, 15 min, 25 kHz.

then increased to 8–20 NTU, finally stabilized around 8 NTU by the end of the 30 d experiment. Similar trend was observed when the intensity was 120 kW/kgDS but the effluent turbidity was higher and finally stabilized around 15 NTU. In the case of intensity of 160 kW/kgDS, the effluent turbidity changed continuously without obvious rule. All samples from SBRs with sludge sonication had an effluent turbidity higher than 10 NTU. Sonication disrupted the sludge structure into small flocs and lysed microorganism cells into small fractions. Small flocs and cell fractions could not settle well and entered the effluent, which contributed to the effluent turbidity.

The intensity of 120 kW/kgDS was the best for SBR sludge treatment considering the excess sludge minimization, sludge SVI, and the effluent quality. Therefore, the sonication intensity of 120 kW/kgDS was used for following experiments. It was unnecessary to further reduce the excess sludge since the excess sludge generation rate was very low (17.8 mg/(L d)). The main purpose of following experiments was to shorten the sonication time in order to save energy.

3.5. Impact of sonication time

Sonication time of 5 min and 10 min was examined. The ultrasound intensity was 120 kW/kgDS and 3/14 sludge was treated. After 30 days operation, it was found that the average excess sludge generation rate was 160.4 mg/(L d) and 114.3 mg/(L d) when the sonication time was 5 min and 10 min, respectively. The high excess sludge was undesirable and thus short sonication was not recommended.

3.6. Sludge organic content

It was reported that without excess sludge discharge 30% of inorganic and persistent hazards accumulated in the wastewater treatment system and slowly deteriorated the system [15]. The VS/SS ratio presents the organic content of the sludge. In this research, the VS/SS ratio did not change significantly. The sludge VS/SS was 0.85–0.88 for the reference SBR without sonication. When sludge was treated by 120 kW/kgDS ultrasound for 15 min, the VS/SS ratio was 0.76–0.90 with an average of 0.84 when the sludge sonication ratio was 1/14, was 0.79–0.88 with an average of 0.83 when the sludge sonication ratio was 2/14, and was 0.82–0.86 with an average of 0.84 when the sludge sonication ratio was 3/14. The stable VS/SS ratio showed that inorganic matter did not accumulate in the SBR because the artificial wastewater contained little inorganic material. When real wastewater is treated, the inorganic materials will accumulate, which demands sludge discharge. Therefore, 100% elimination of extra sludge is impossible for real wastewater treatment.

3.7. Phosphorous removal

Fig. 6 showed that the effluent TP for all samples with sonication was much higher than that of the blank SBR. Theoretically, the P-removal bacteria absorb P in the aeration period and release P in the anaerobic period. P is removed from the SBR via effluent and excess sludge discharge. Without sludge discharge, all P left the SBR via the effluent, and the biological P-removal was zero [4,6]. Extra chemical P-removal would be needed to reduce the effluent P concentration in order to meet the discharge standard. P may also be recovered in the process [5].

Mass balance of phosphorous showed that in this study 83% of TP was discharged via the effluent, but the effluent TP level was not stable, indicating unstable metabolism of the P-removal bacteria. When sonication was integrated into the SBR system, the excess sludge was greatly reduced, and the responding SRT was very long. When 3/14 sludge was treated by 120 kW/kgDS ultrasound for 15 min, the average excess sludge generation rate was 17.8 mg/(L d) and the responding SRT was 112 days. Microorganisms with long generation time have advantages to dominate the activated sludge system when SRT is long. However, the phosphorous-removal bacteria have short generation time and thus may be in disadvantage in the SBR when the SRT increases. Sludge samples were taken from the SBRs to examine the TP content of the sludge. The TP for the blank SBR sludge was 37.2 mg/L while TP of sludge from SBR with sonication was 37.9 mg/L, and the difference was within the analytic error. Therefore, the P-absorption ability of the sludge in SBR was not altered by the sonication and recycle of partial sludge.

3.8. Energy analysis

When 3/14 sludge was treated by ultrasound (120 kW/kgDS) for 15 min, the amount of excess sludge from SBR was reduced by 91.1%. Since the MLSS in the SBR was 2000 mg/L and the hydraulic retention time within the SBR was 6 h, the energy consumption was calculated to be 3.21 kW h/m^3 (in term of wastewater).

4. Conclusions

Experiments showed that ultrasound effectively disintegrated the activated sludge and increased the SCOD. The sonicated sludge could then be returned into SBR as substances for biological oxidation in the aeration tank. The excess sludge production was almost eliminated when 3/14 sludge was treated by ultrasound (intensity higher than 120 kW/kgDS) for 15 min. The sound intensity of 120 kW/kgDS was best since the SBR sludge and effluent were of high qualities. The COD removal ratio was 81.2%. Short sonication time was inefficient in excess sludge reduction. The SBR sludge P-adsorption capacity did not change but the effluent TP increased due to the elimination of sludge discharge. Long term run and microorganism analysis should be done to examine the stability of the sludge reduction approach.

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