Municipal sludge characteristic changes under different aerating condition in a deep-shaft aeration system
Jiaqing Xiong, Xiaochang C. Wang, Wei Shu, Teng He and Yanzheng Liu

ABSTRACT
A pilot-scale municipal sewage sludge deep-shaft aeration system was implemented in Lanzhou, Gansu Province of China. The reactor depth was 60 m with a diameter of 1.0 m and the sludge to be treated came from a wastewater plant in Lanzhou. In order to obtain the optimum operation conditions, analysis was conducted on the transformations of the volatile suspended solids (VSS), temperature, pH, oxidation-reduction potential (ORP) and pathogens in the deep-shaft reactor under different aeration conditions. Attention was paid to how operating conditions affected the removal efficiency of the VSS and the reaction temperature. As a result, higher volatile solids removal was gained at higher temperature, and the temperature could reach 50.8°C for a complete inactivation of bacteria in the first reaction zone when the deep-shaft aeration system was run for about 18 days. The sludge aeration rate was observed as 1.5 to 1.8 L/(h·L sludge) which enabled the volatile solids removal rate to reach 40.1%. The degradation of VSS occurred under a micro-oxygen environment, and the lowest ORP was found to be −256 mV in the digestive process. Not only aerobic bacteria but also anaerobic and facultative bacteria performed their functions in the reactor.

Key words | aeration intensity, deep-shaft aeration, reaction temperature, sludge, volatile solids removal efficiency

INTRODUCTION
Sludge from municipal sewage treatment plant contains lots of toxic ingredients such as biodegradable organics, heavy metals, inorganic particles, pathogens and parasite eggs in addition to large amounts of water (He et al. 2014). As a product of the sewage treatment process, the sludge contains a lot of water and organics which can easily degrade (Cusidó & Soriano 2011). Due to its complex composition and properties, sludge disposal is often difficult and challenging. If the untreated sludge is arbitrarily stacked or discharged, it will seriously influence the surrounding ecological environment (Li et al. 2013; Samolada & Zabaniotou 2014). Therefore, development of a safe and economic method for the disposal of the sludge from municipal sewage treatment plant is required. With the continuous increase of sewage treatment facilities in many countries, the sludge production is increasing. According to statistical data in China, by the end of 2012 more than 3,100 sewage treatment plants were constructed and put into operation. The design capacity of these sewage treatment plants amounted to 139 million m³/d, which would generate 20 million tons of sludge (with moisture content as 80%) each day. However, less than half of these plants were equipped with sludge disposal facilities in the existing sewage treatment plants in China. Therefore, the sludge produced by many facilities has not been safely and effectively treated. Of the sludge disposal facilities, composting and incineration account for 14.2% and 14.8%, respectively, while the rest are mainly landfill. As the moisture content of the dewatered sludge is usually higher than 75%, sanitary landfill is very difficult (Niu et al. 2013). In recent years, a variety of sludge treatment technologies have been widely adopted, such as aerobic digestion, anaerobic digestion, aerobic composting, lime stabilization, sludge drying and deep-shaft aeration (Peeters et al. 2014; Scaglia et al. 2014). Among them, the deep-shaft aeration sludge treatment, as an energy efficient auto-thermal aerobic digestion method, has drawn attention because it can be run under high temperatures without supplemental heat input. The realization of the high temperatures relies mainly on the heat produced by microbial metabolism and compressor running. This process often occupies less construction area, with
high oxygen transfer efficiency, and can perform fast and efficient sludge disposal. Compared with the conventional aerobic sludge treatment process, the deep-shaft aeration sludge treatment often shows its advantages of small land occupation, low operation cost, low investment, and low sludge disposal costs. The deep-shaft biological technique has already been applied for the treatment of municipal wastewater (Polprasert & Raghunandana 1985; Grän-Heedfeld et al. 1995; Giovannettone et al. 2009), pretreatment of landfill leachate (Niu et al. 2013), and treatment of municipal sludge (Grän-Heedfeld et al. 1995; Zerlottin et al. 2013) and aqueous hazardous waste (Lovo et al. 1990). However, little information is available regarding the treatment of sewage sludge using the deep-shaft bioreactor, except for an American study in which the primary sludge and residual activated sludge were disposed of by the deep-shaft process to meet the Class A biological solid standard set by the US Environmental Protection Agency, and the treated sludge was directly used as a soil fertilizer.

Due to lack of practical experiences in China, this study was conducted as a first trial for the application of the deep-shaft aeration sludge treatment technology by installing a pilot system at the Saltworks Sewage Plant in Lanzhou, Gansu Province, in Northwestern China. The system was run under a batch operation mode with continuous monitoring of the reactor temperature, pH, mixed liquor suspended solids (MLSS), volatile suspended solids (VSS) and oxidation-reduction potential (ORP). Attention was paid to how the related operating condition might influence the VSS removal efficiency along with temperature increase in the reactor. The feasibility of using deep-shaft aeration to treat urban sewage sludge is also discussed.

MATERIALS AND METHODS

Experimental setup

The pilot-scale system was constructed at the Saltworks Sewage Treatment Plant in Lanzhou, Gansu Province, China. The equipment was 60 m deep and with a diameter of 1.0 m. A process flow diagram for the pilot-scale facility is shown in Figure 1. The diameter of its outer barrel was 1,000 mm (60 m long) and that of the inner tube was...
500 mm (25 m long). The effective volume of the deep-shaft reactor was 47.1 m$^3$. The design capacity of sludge treatment was 7.5 m$^3$/d (for sludge with moisture content of 96%) and the practical treatment scale was $Q = 7.5 – 12.5$ m$^3$/d. The getter pool was placed on the ground and the well bore was placed underground because the follow-up sludge treatment equipment (one-piece air floating device) was installed on the ground. The gas stripping process requirement of mud could run without a pump suction. The net size of the getter pool was 2.0 m in height with a diameter of 2.0 m. The effective volume of the getter pool was 14.13 m$^3$. The inner and outer tubes were made of carbon steel with a thickness of 10 mm. Insulation material was filled with thick insulation foam concrete with a thickness of 200 mm between the outer cylinder wall and the concrete wall. The entire deep-shaft reaction zone was divided into three different reaction areas with three aeration devices, as shown in Figure 2. A cyclic aerator was set at 32 m in depth and disc aerators were located at depths of 51 m and 59 m, respectively. The cyclic aerator was used to circulate the sludge in the reactor in the startup stage. The first reaction zone (oxidation zone) was located in the upper reactor (0–32 m), including a concentric loop piping and a circulation area for mixed sludge cycle. The second reaction area was a mixing zone (32–51 m), with a toothed disc aerator intensively mixing air with the sludge. The third reaction area was a deep oxidation zone at the lower part of the reactor with a toothed disc aerator (51–60 m). The aeration air compressor was equipped with three 22kW screw compressors (dual-use equipment), and the air supply line was equipped with a regulator device and flow measurement and control device.

The method of test

Sludge for the experiment

The sludge for the experiment came from the mixed sludge and dry sludge after dehydration from the concentrated tank of the sewage treatment plant. The sludge for the experiment was homogeneously mixed and distributed in the equalization basin. The sludge solid content was 5 to 6%, the suspended solid concentration was 50.4 to 62.1 g/L, the VSS concentration was 18.5 to 27.5 g/L and the pH was from 6.6 to 7.0. Considering that the sludge from the sewage plant had relatively low organic component (Table 1), a certain amount of wheat flour (containing 7–14% protein, 63–72% starch, 4–5% non-starch polysaccharides and 1% lipid) was added to the reactor in order to adjust the sludge organic content in the experimental process.

Startup of the experiment

The experiment was conducted under batch operation mode and operated continuously for 24 days without sludge input and output in order to investigate the relationship between the aeration and the removal efficiency of organic matter in the deep-shaft aeration reactor. The reactor was fed with the sludge with solid content of 5 to 6% and an effective volume of 60 m$^3$. The reactor was controlled by the aeration valve of the air delivery pipe connected to the reactor from the air compressor. During the experiment air was continuously supplied until the highest temperature was reached. After this operation cycle, three-quarters of the volume of the sludge was discharged from the reactor while only one-quarter was reserved in the reactor as seed sludge for the next batch operation cycle for sludge treatment.

Analytical parameters and methods

Sludge samples were taken from the reactor daily and transported to the laboratory for analyzing a number of parameters such as temperature, pH, MLSS, VSS, ORP and the number of pathogens. All these analyses were repeated three times. The measurements of temperature,
pH, MLSS and VSS followed the Chinese standard methods (CJ/T 221–2005). Considering the dissolved oxygen could not be accurately measured for the sludge with high solid content, ORP was used as an alternative parameter to reflect the dissolved oxygen demand in the digestive system. It was measured three times using a digital ORP meter because the ORP might fluctuate, and the average ORP and its fluctuation range were recorded for data analysis (Coma et al. 2015). The determination of pathogenic bacteria was based on the detection of fecal coliforms and salmonella following Chinese standards.

RESULTS AND DISCUSSION

Temperature variation in the reaction zone

Figure 3 shows the variation in the first reaction zone of the reactor. The temperature rose gradually up to a maximum temperature of 50.2 °C on the 18th day, and then decreased gradually with the digestion process in the reactor because the degradable organics was reduced and less heat was released. The ambient temperature was almost unchanged at about 21 °C. The reactor was cooled rapidly under a high aeration rate at 2.5–2.8 and 3.5–3.8 L/(h·L sludge), and slowly under a lower aeration rate at 1.5–1.8 L/(h·L sludge) in the later stage. The heat was taken away by gas emission, and the lower the aeration rate was, the less the heat dissipation was. It is an indication that the heat of the system mainly came from the oxidation of organics in the sludge. When the sludge in the reactor was under a high total solids (TS value), there was a high VSS value correspondingly. As a result, the heat energy that microbial endogenous metabolism released was higher, and the system temperature warmed up so fast that a higher digesting temperature was achieved in the reactor. On the other hand, the thermophilic digestion system could accelerate the degradation of VSS in turn so that the time of sludge stabilization was enormously shortened. However, when the sludge concentration was extremely high, its viscosity increased, mobility descended, and the oxygen transfer efficiency reduced significantly with a downtrend of VSS removal. In China, sewage sludge has less than 70% of organic matter content in most sewage treatment plants. It is thus very feasible that, if the deep-shaft aeration system is used for sludge stabilization treatment, VSS concentration of the feeding sludge can be appropriately enhanced to ensure the oxidative decomposition of organic matter, to release sufficient heat and keep the digestive system at a self-thermal high temperature state (Rybicki 2014). In this experiment an appropriate amount of flour was added to increase the concentration of VSS. Because the deep-shaft aeration system was not completely self-heating, part of the heat is maintained by the high temperature coming from compressing air supplied by the air compressor. The air temperature in the outlet of the air compressor reached 75 °C in the experiment. Therefore, the heat of the deep-shaft aeration reactor was not only from VSS degradation but also from surplus heat of the air compressor.

**pH and ORP variations in the first reaction zone**

As shown in Figure 4, pH varied similarly under three aeration conditions in the digestion system. The pH decreased...
slightly after the deep aeration reactor started, reached its minimum value in 2 or 3 days, and then went upward. After 10 to 11 days, the pH of the reaction system was higher than 7.0, and fluctuated slightly in the weak alkaline range. The system temperatures were low during its early startup period and the pH fell slightly as a result of hydrolysis acidification of organic in sludge. As the temperature gradually increased, the nitrification process was restrained, and organic nitrogen in sludge turned into ammonia and went into the supernatant, leading to a rise in pH value. In the late phase of nitrification, ammonia gas was continuously blown out through the aeration. The digestive system maintained a weak alkaline state under the action of acid-base balance.

Figure 5 shows that ORP varied in a similar tendency under three different aeration rates in the digestion systems. In the first 8 days, all ORPs of the digestion systems rose at first and then decreased. During 9 to 15 days, all ORPs in the digestion systems were maintained at a low value (about −256 to −160 mV) with certain fluctuations. After 16 days, all ORPs increased again and gradually reached above 0 mV. On the 24th day, ORPs were 70, 82 and 91 mV, respectively, under aeration intensity of 1.5–1.8, 2.5–2.8 and 3.5–3.8 L/(h·L sludge). Although constant aeration intensity was maintained during the experiment period, the ORP in the digestive system fluctuated in the range of −180 ± 50 mV mostly, except when it was steadily above 0 mV in the later stage. The variation of the ORP indicated that the sludge stabilization process of deep-shaft aeration was not a completely aerobic condition, and a number of anaerobic bacteria and facultative bacteria existed in the reactor. Sludge concentration was high in the initial stage of batch runs, and the dissolved oxygen would be deficient because of the large amount of organics which transferred to easily biodegradable matter, so that anaerobic bacteria and facultative bacteria appeared. Microbial population diversity would be beneficial to the degradation of VSS, which helped the reactor to maintain a high temperature.

Pathogen inactivation in the first reaction zone

Harmless treatment of sludge aims to kill or inactivate pathogenic microorganisms growing in the sludge, so as to make the sludge safe to people, animals and the environment. The fecal *Escherichia coli* and salmonella were selected as indicators of pathogenic bacteria in the experiment. In the stage of sludge batch runs VSS was 38.5 g/L and aeration intensity was 1.5–1.8 L/(h·L sludge). The ORP in the digestive system was 50.4 mV, which probably implies that the temperature is not much higher than in the test reactor because the sludge was harmless in the deep-shaft aeration reactor because the pathogen inactivation rate could reach 100%. Other studies have also shown that the inactivation temperature of fecal *Escherichia coli* and salmonella was 55°C within 1 h (Singh et al. 2011). The highest temperature in the first reaction zone of deep-shaft aeration was 50.4°C, which probably implies that the temperature of the mixing zone and deep reaction zone is much higher than in the first reaction zone. On the other hand, this result may indicate that the temperature is not the only reason for inactivating pathogenic microorganisms (Bowen et al. 2014). The rise of pH and the increase of the

<table>
<thead>
<tr>
<th>Reactor temperature (°C)</th>
<th>Fecal <em>Escherichia coli</em> (MPN/g TS)</th>
<th>Salmonella (MPN/4 g TS)</th>
<th>pH</th>
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</thead>
<tbody>
<tr>
<td>Digestion time (d)</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>0</td>
<td>26.4</td>
<td>4.1 × 10⁷</td>
<td>15</td>
</tr>
<tr>
<td>10</td>
<td>35.3</td>
<td>1.9 × 10⁵</td>
<td>9</td>
</tr>
<tr>
<td>18</td>
<td>50.2</td>
<td>not check out</td>
<td>not check out</td>
</tr>
<tr>
<td>24</td>
<td>46.3</td>
<td>not check out</td>
<td>not check out</td>
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Table 2 | Pathogen inactivation
concentration of ammonia nitrogen may also promote the pathogenic bacteria to be inactivated. The activity whereby pathogenic bacteria are inactivated may also be associated with the internal environment of the reactor, such as pH, sludge age and sludge digestion time. In short, it is obvious that pathogenic bacteria were inactivated in the deep-shaft aeration sludge digestion system. Because the pathogens have a potential to grow again during the process of storage and transportation of the digested sludge, maintenance and preventive measures would be necessary.

VSS concentration variations in the reactor zone

With the progress of sludge digestion, VSS concentrations under different aeration intensity varied greatly as shown in Figure 6. When the digestion proceeded continuously for 10 days, the VSS concentration varied by 17.3, 22.1 and 21.3%, respectively, under the supply conditions of 1.5–1.8, 2.5–2.8 and 3.5–3.8 L/(h·L sludge). When the digestion time was 20 days, the VSS concentration varied by 35.2, 39.3 and 38.3%, respectively, under these aeration conditions. The digestive systems with aeration rates of 2.5–2.8 and 3.5–3.8 L/(h·L sludge) could realize a VSS removal efficiency higher than 38% (Class A sludge stabilization requirements). The digestive system with aeration rates of 1.5–1.8 L/(h·L sludge) could not meet the requirement in 20 days. However, when the digestion time was 22 days with aeration of 1.5–1.8 L/(h·L sludge), the VSS removal efficiency in the digestive system could reach 38.7%. Therefore increasing aeration rate would help to shorten the residence time of the sludge digestion process. Based on the these results, the rate of VSS concentration variation was only about 3.5% different between the aeration conditions of 1.5–1.8 L/(h·L sludge) and 3.5–3.8 L/(h·L sludge). This suggests that aeration within a certain range of aeration intensity would have little influence on the digestive effect, and the excessive aeration would lead to a large amount of gas to be expelled from the reactor and make the system cool quickly, which would not benefit the realization of sludge self-heating temperature state. Therefore, the deep-shaft aeration sludge treatment system with 1.5–1.8 L/(h·L sludge) aeration intensity would be more appropriate to sludge self-heating digestion. This aeration intensity can also keep a normal fluid circulating condition in the reactor to avoid producing the backflow situation. In addition, Figure 6 shows that the VSS concentrations of the three digestive systems changed slowly in 8–14 days under the aeration intensity of 1.5–1.8, 2.5–2.8 and 3.5–3.8 L/(h·L sludge), respectively, when the rate of change in concentration values was 18.5–21.5, 21.3–24.8 and 20.5–25.9%. It indicates that the solid organic in sludge can gradually reduce with the gradual increase in temperature after the sludge digestion process starts. When thermophilic bacteria proliferate, the VSS content of the sludge digestion system would begin to slowly decline with the increasing of total amount of thermophilic microbial cell body. As a result, the VSS concentration rate would change slowly. After the dead cells and available organic substrates have been decomposed completely, thermophilic microorganisms come into their endogenous respiration stage, and the VSS content of the digestive system will continue to decline due to reduction in the total body of thermophilic bacteria.

CONCLUSIONS

- In the pilot-scale deep-shaft aeration sludge treatment system, the solid content of the original sludge should be controlled at 5 to 6%. When the solid content is too low, the VSS content is not enough to generate the heat to maintain a normal heating need. On the other hand, too much solid content is likely to result in internal anaerobic oxidation and render the sludge unable to flow easily, which will further influence the running of the system. The temperature in batch experiments can reach above 50 °C on the 18th day. Meanwhile, the concentration of original sludge influences the heating-up of the reactor. The removal of the VSS is also influenced by the reactor temperature. The higher the temperature is, the greater the VSS removal efficiency is.
- It is appropriate that sludge aeration intensity is 1.5–1.8 L/(h·L sludge) for the VSS concentration of 38.5 g/L, in which the VSS removal efficiency could reach 40.1%. When the digestion in the batch experiment trial lasted 20 days, the sludge can be stabilized. After
stabilization the VSS removal efficiency would rise more slowly. The aeration intensity influences the self-heating process of the deep aeration reactor. Too large an aeration intensity would easily lead to excessive heat dissipating and lead to low reaction temperature and the temperature to drop rapidly. Too low an aeration intensity would easily lead to oxygen being insufficient for digesting the sludge in the reactor so that microbial activity is poor and the reaction temperature rises slowly.

- Research shows that a micro-oxygen environment is conducive to VSS degradation by monitoring ORP of the reactor. There is not a completely aerobic state in all zones of the deep-shaft aeration reactor. In addition, anaerobic and facultative bacteria in the reactor promote the hydrolysis acidification rather than produce methane. A micro-aerobic environment is conducive to transform a lot of organic matter into volatile organic acids, and aerobic bacteria can be quickly utilized to increase VSS removal efficiency. Thus, it is necessary to meet microbial oxygen demand and save energy by adjusting the aeration intensity.

- Compared to the general medium temperature digestion, the VSS removal rate is faster and the inactivation effect on pathogenic bacteria is better in the high temperature sludge digestion system. The pathogen inactivation was dependent not only on environmental temperature but on pH, sludge retention time and digestion period.

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