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Performance of direct anaerobic digestion of dewatered sludge in long-term operation

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ABSTRACT

Direct anaerobic digestion of dewatered sludge with total solids (TS) content of 15–20% was tested in a horizontal digester for one and half years. The system kept stable with pH 7–8. The concentration of volatile fatty acids was lower than 800 mg/L, free ammonia nitrogen was lower than 200 mg/L, and total alkalinity kept higher than 6000 mg/L. The performance was influenced by organic load rate (OLR) and organic content in feed sludge. When volatile solids (VS) in TS of feed sludge reached 60–65% at OLR 3.50–3.70 g/(L·d), the process exhibited the best performance with organic removal rate of 32.19 ± 7.73% and methane production of 156.86 ± 13.05 ml/g VS added. Microbial analyses indicated that *Methanosarcina* became predominant and *Methanosaeta* almost disappeared. Moreover, hydrogenotrophic and methylotrophic methanogens accounted for 18.13–29.40% and 11.58–29.56% of the total, respectively. These provide a new guideline for small-scale or centralized sludge treatment.

1. Introduction

Waste activated sludge is the key solid waste discharged from biological wastewater treatment processes. Its quantity is increasing rapidly in many developing countries like China because wastewater collection system is improved and more wastewater is cleaned (Zhen et al., 2015). Sludge has become a key issue for these wastewater treatment plants (WWTPs) since it contains water, perishable organics, pathogens, and sometimes heavy metals and other hazardous materials. Thus, many technologies have been developed to eliminate the potential risk of sludge to environment and human beings. Anaerobic digestion, composed of three biochemical reactions including fermentation, acetogenesis and methanogenesis, is a widely-used pathway to reduce sludge volume and mass, inactive pathogens in sludge and simultaneously convert organic matter to biogas as bioenergy source (Cheng et al., 2016). In WWTPs, primary sludge and excess sludge are commonly mixed and thickened at first, and then the thickened sludge was fed into digesters for biogas production. Finally, the digested sludge is dewatered mechanically and then used for further treatment or disposal. In general, the specific biogas production of sludge can reach 500–750 ml per gram volatile solids (VS) added (Appels et al., 2008). Biogas is composed of 50–70% methane and 20–40% carbon dioxide, and its heat value can reach 23–25 MJ/m^3 (Appels et al., 2008). When biogas is burned for combined heat and power production, the heat can meet the requirement of digesters and the residual energy can be output for extra income.

The situation is different in some small WWTPs and old WWTPs in China. For small WWTPs, sludge production is commonly quite low and cannot support sludge anaerobic digestion process economically. For some old WWTPs, there is no enough space for digesters. Thus, centralized digestion facilities have to be built outside of WWTPs, and thickened sludge is first dewatered and then transported from WWTPs to digesters at other sites. The water content of dewatered sludge is around 80%, but the water content of feed sludge is commonly controlled at 94–96% for conventional anaerobic digestion. Thus, before fed into digesters, dewatered sludge should be diluted using a large amount of water. After anaerobic digestion, the digested sludge needs the re-dewatering procedure. To save the energy and water consumed on dilution and dewatering, high-solids anaerobic digestion (HSAD) could be an alternative approach.

With high-solids feedstock, HSAD can reduce the volume of digesters, save water and decrease the wastewater discharged from re-dewatering. Moreover, it can reduce the energy consumption on heating feed sludge and digesters (Liao and Li, 2015). HSAD has ever been applied to organic fraction of municipal solid waste (Bolzonella et al., 2006), agricultural waste (Shi et al., 2013), yard waste and food waste

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(Brown and Li, 2013). Nevertheless, it is rarely used to sludge alone because high-solids sludge acts as thixotropic fluid with high viscosity (Cheng and Li, 2015). The blocked mass transfer would possibly result in accumulation of some intermediate products, depress microbial activity and decrease biochemical reaction efficiency (Liao et al., 2014; Liu et al., 2016). In fact, without agitation, total solids (TS) content of 6% could be the boundary between low-solids and high-solids anaerobic digestion, and methane yield decreased exponentially when TS increased from 6% to 15% (Zhang et al., 2015). When batch experiments were carried out in warm shaking bath, the performance of HSAD was improved but the digestion time was still prolonged significantly (Liao et al., 2014). Therefore, the efficiency of mass transfer in sticky sludge is quite low (Zhang et al., 2016), and enhanced agitation is necessary for HSAD. It was ever reported that HSAD achieved similar results with conventional anaerobic digestion when it adopted a stirring system composed of a frame agitator and three oblique blades (Liao and Li, 2015). In general, the concentrations of volatile fatty acids (VFAs) and ammonia in HSAD systems were much higher than those in conventional anaerobic digestion, but HSAD can keep steady with high resistance to some common inhibitors (Duan et al., 2012; Liao and Li, 2015). The phenomenon should be attributed to the evolution of microbial community structure, and some hydrogenotrophic methanogens replaced acetoclastic methanogens (Liu et al., 2016).

Several HSAD projects have been put into practice in China, for example, Xiajiahe sludge treatment plant with feed sludge TS 10% at Dalian City, and centralized sludge treatment plant with feed sludge TS 15% at Kunming City. Besides these, some projects of HSAD combine thermal hydrolysis pretreatment like Changsha sludge treatment plant. Nevertheless, sludge concentration of the current projects and the relevant researches is commonly limited at 10–15% because conventional cylindrical or oval reactors with different paddle agitators cannot deal with dewatered sludge with TS higher than 15% directly. In fact, sludge viscosity increases exponentially with TS. Low-solids sludge with TS 2–6% was nonthixotropic pseudoplastic fluid, high-solids sludge with TS 7–15% evolved to thixotropic fluid, and dewatered sludge with TS 15–25% became viscoelastic semi-solid (Cheng and Li, 2015). Thus, dewatered sludge, which is transported from WWTPs to centralized sludge treatment plants, has to be diluted to TS 10–15% so as to keep sludge flowable before fed into digesters.

To avoid dilution, a new type of anaerobic digestion system should be developed. Although dry anaerobic digestion with TS greater than 20% was developed before, this process was only applied to loose wastes such as organic fraction of municipal solid waste, crop wastes or their mixture with sludge (Karthikeyan and Visvanathan, 2013; Zhang et al., 2014). However, up to date, direct anaerobic digestion of dewatered sludge has been rarely studied. Duan et al. operated a digester with dewatered sludge (TS 18%) as the feedstock, and the methane yield reached 150–200 ml/g VS added with the help of helix-type stirrers (Duan et al., 2012). In spite of good results, the energy consumption on stirring and heating was not mentioned in this work. Hidaka and Tsumori tested the digestibility of sludge with TS 5–20% and found substrate concentration 10–20% resulted in unstable performance with accumulation of VFAs (Hidaka and Tsumori, 2014). In fact, the specific biogas production was only 100–200 ml/g VS added when fed with dewatered sludge (Hidaka et al., 2016). However, the other key influencing factors, like stirring mode and organic load rate (OLR), were not considered in the research. Hence, the existing knowledge cannot support the assessment of direct anaerobic digestion of dewatered sludge.

To fill the knowledge gap, a laboratorial-scale horizontal anaerobic reactor was applied to direct anaerobic digestion of dewatered sludge in this study. The digester was operated in a long term of one and half years. During the period, the relevant operational conditions were optimized and the performance of this process was analyzed including stability, biogas production, organic removal rate and microbial community structure. Particularly, the energy input and output were discussed. The results can provide a comprehensive view on the performance of this new process.

2. Materials and methods

2.1. Dewatered sludge

The dewatered sludge collected from a local full-scale municipal WWTP was directly used as the feed sludge of the horizontal high-solids digester. In this plant, a biological aerated filter process was applied to clean the wastewater. The discharged sludge, composed mainly of primary sludge with a small amount of biofilm sludge, was conditioned with polyacrylamide and dewatered to a water content of about 80% by centrifugation. Due to the varied influent wastewater, the total solids concentration and the organic content of dewatered sludge fluctuated over time, but the ratio of C/N remained at 7–9. Hence, TS and VS of the feed sludge were recorded every day during the experiments.

2.2. Anaerobic reactor

The horizontal digester with twin helical ribbon stirrers was shown in Fig. 1. The inside diameter was 300 mm, the length was 290 mm and the volume was 20 L. The surface area was about 0.45 m^2. The diameter of the stirrer was 280 mm, the pitch was 140 mm, the width of the impeller was 30 mm and the thickness of the impeller was 12 mm. A screw pump and the combination of a spiral conveyer and a screw pump were applied to sludge feeding and discharging, respectively. The spiral conveyer was also operated together with the helical ribbon stirrers, thus it can function as an auxiliary blender and reduce the dead zone of stirring in the digester. The system was enveloped by water bath, which was kept at 35 °C using automatic electric heating.

Before anaerobic digestion experiments, the digester was numerically simulated using the software FLUENT preliminarily. The density of the digestate was about 1.05 g/ml and the viscosity was about 10 Pa·s. During the simulation of the reactor, an unstructured mesh arrangement with hexahedral elements was applied to generate about 643200 meshes, and the mixing zone was processed by multiple reference series. Laminar flow model and its relevant parameters used the fault values in the software, and the semi-implicit algorithm was adopted. Based on the simulation, the time required by complete mixing was estimated after dewatered sludge was fed into the digester (Wu, 2010), and the optimal stirring mode including speed and duration was determined. The mixing degree (M_t) can be calculated by the following equation.

$$M_t = (C_t - C_{ave})/C_{ave} \times 100\% \quad (1)$$

where, C_t is the solid concentration in the mesh where feeding sludge at time t and C_{ave} is the average solid concentration of the whole reactor. When M_t decreases lower than 5%, the system is recognized as homogeneous.

At the start-up stage of anaerobic digestion experiments, about 17 kg dewatered sludge and inoculum from other digesters were put into the digester together. Every day about 0.5 L of digested sludge was discharged and then the same volume of dewatered sludge was fed. Sludge retention time (SRT) of the digester was kept around 30 days. The characteristics of feed sludge, digested sludge and biogas were detected. In addition, the structure of microbial community was also analyzed. After about two month, the system became steady and the data were used to evaluate the process.

2.3. Analytical procedures

Digestate samples were directly used to analyze the general parameters, such as TS, VS and C/N ratios. To analyze soluble parameters, digestate samples were centrifuged at 8000 rpm (6700g) for 10 min and then the supernatant was filtered by membranes with mesh size of