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Investigation of the effect of intermittent minimal mixing intensity on methane production during anaerobic digestion of dairy manure

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ABSTRACT

Mixing plays an important role in maintaining the solids suspended and the fermenting liquid homogeneous throughout the digester, which helps to improve methane production. The pilot-scale digester with working volume of 1 m^3 was mixed with a top-driven impeller. Three mixing intensities, 50, 100 and 150 rpm were minimally intermittent mixed once a day for 5 min under mesophilic temperature conditions (35 ± 0.3 °C) with average total solids content of 14.1% and hydraulic retention time of 30 days. The results show that 100 rpm mixing intensity outperformed the other two, indicating that mixing intensity threshold exists and beyond which methane production is negatively affected. However, 50 rpm was regarded as the economical mixing intensity even though dead zones were recorded. Minimally intermittent mixing once a day was enough to maintain anaerobic digestion process and performance efficiency for optimum methane production. Computational fluid dynamics (CFD) results agreed with the experiment, demonstrating that 100 rpm mixing intensity was sufficient to homogenize the digester content. Further, CFD was used to predict the mixing time in the digester.

1. Introduction

Anaerobic digestion (AD) is an attractive biotechnology for the treatment of organic wastes and livestock manure. Anaerobic microorganisms transfer bioenergy stored in biological materials into biogas in the absence of oxygen, which involves four sequential steps: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The digestion process leads to the formation of biogas (a mixture of carbon dioxide and methane) and microbial biomass. However, this process is difficult to control and should be optimized. In general, many factors affect the biogas yield and methane concentration such as fermentation materials, volatile solids (VS) concentration, temperature, pH, hydraulic retention time (HRT), mixing, organic loading rate (OLR), and so on. There are many significant advantages of AD, including a low energy requirement and energy harvesting (Ghosh and Pohland, 1974). More and more agricultural and industrial operations are using anaerobic digesters to degrade soluble organic wastes, especially wastewater plant and dairy farms utilizing organic materials to produce biogas, which not only reduces the pollution potential but also improves the utilization efficiency of energy. However, there are some problems encountered in AD, for example, poor stability of operation and low methane yield, which prevent this technique from being widely applied (Dupla et al., 2004). Some of these problems can be solved by appropriate mixing in the digester.

Mixing can be accomplished with the following methods: mechanical agitation, recirculation of digesters liquid contents and gas sparging. Mechanical agitation is considered as the most efficient way at the same energy consumption (Wu, 2010; Lindmark et al., 2014a,b). The importance of mixing in achieving efficient substrate conversion has been noted by many researchers, while the optimum mixing pattern is a subject of much debate (Karim et al., 2005a, b; Wu, 2014; Wiedemann et al., 2017; Kress et al., 2018). Many researchers discovered that gas production is not affected by just changing the mixing intensity. Stafford (1982) reported that there was no improvement in gas yields for impeller speeds between 140 and 1000 rpm in a digester system treating sewage sludge. Deublein et al. (2008) presented that microorganisms are sensitive to mixing intensity and may not survive an excessive mixing intensity. Hoffmann et al. (2008) found that different mixing intensities had no effect on the biogas production rates and yields under steady-state conditions.

Dague et al. (1970) compared continuous mixing with intermittent mixing using liquid municipal waste. The latter was found to improve gas production. Stroot et al. (2001) showed that continuously mixed digesters performances were unstable at higher OLRs, while intermittent minimally mixed digesters performed well for all the OLRs ranging from 3.5 to 9.4 g VS/L d operated under mesophilic conditions

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(37 °C) and an initial 20-day HRT. McMahon et al. (2001) did some experiments confirming that continuous mixing was not a good choice for good digester performance. They observed that higher loading rates inhibited digestion, and that a reduction of mixing levels was regarded as a good method to stabilize unstable digesters. Kim et al. (2002) checked the performance of continuous stirred-tank reactors (CSTRs) and intermittent minimally mixed (manually mixed before wastage and immediately after feeding) digesters, and reported that under steady state operations with both a low and an increased OLR, the lowest biogas production was recorded in the CSTRs, while the intermittent minimally mixed recorded the highest biogas production at both mesophilic (35 °C) and thermophilic (55 °C) temperatures. Karim et al. (2005b) claimed that unmixed and mixed digesters performed quite similarly when the total solid (TS) of the manure was low (5%). However, the effect of mixing became important when the digesters were fed with thick manure slurry (10% and 15% TS). They also realized that the recirculation system was not effective when the TS was 15% under the same experimental conditions. Kaparaju et al. (2008) compared continuous mixing with intermittent mixing in a pilot-scale digester, and showed an average increase in biogas yield of 7% during intermittent mixing (5 min on and 5 min off). However, stratification of solids occurred at the top and bottom with intermittent mixing, which did not affect the performance and could be an operational strategy for maintaining a higher solid retention time (SRT) by discharging from the middle layer. Kowalczyk et al. (2013) proposed that intermittent mixing could produce more biogas than continuous mixing at the beginning of the digestion process and varied mixing later in the process. However, the methane content was not significantly influenced by the mixing mode. Their work supported that optimized intermittent mixing and feeding could improve AD efficiency over a CSTR. Lindmark et al. (2014a) suggested that intermittent mixing could be a better method than continuous mixing. It could not only decrease the maintenance and energy demand of the process, but also produce the same amount of biogas and even improve gas production. Kariyama et al. (2018) conducted a comprehensive review on the influence of mixing on AD efficiency. They claimed that there was no motivation to continue to operate stirred tank anaerobic digesters as CSTRs if AD energy efficiency was improved, and that AD energy production efficiency could be achieved with optimized intermittent mixing. They also concluded that intermittent minimal mixing was enough to maintain the process and performance efficiencies of AD in daily batch-fed digesters. Based on the literature review, in this study the experiments with three different mixing intensities for a constant mixing time were conducted for only intermittent minimal mixing once a day during feeding, in which effluent was discharged from the middle layer before feeding to ensure a long SRT which improves methane production.

With the development of computational fluid dynamics (CFD) technology, more and more researchers investigate the effect of mixing on anaerobic digestion and optimize the mixing scenario. Bell–Mendoza et al. (1998) modeled the effect of a completely mixed regime and an incomplete mixing on anaerobic digestion. The digester volume was split into two regions (the flow-through and the retention regions), in which the transfer of material between the two regions was assumed to be limited. The deviations from an ideal completely mixed regime were represented by changing the relative volume of the flow-through region and the turnover time of material in the digester. Evaluating the impact of the mixing parameters from the simulation results demonstrates that the flow-through region has a significant impact on the performance of AD even though both mixing parameters are important for the overall AD efficiency. In addition, their results showed a decline in methane production due to incomplete mixing. Keshtkar et al. (2003) redefined the conditions provided by Bell–Mendoza (1998), in which the turnover time of material in the digester was replaced by the ratio of the internal exchange flow rate to the feed flow rate. Their results were like the findings of Bell–Mendoza (1998). Wu (2011) investigated turbulence models for mechanical agitation of non-Newtonian fluids in anaerobic digesters and proposed that the standard $k-\omega$ and the realizable $k-\varepsilon$ models could be better than other turbulence models. Bridgeman et al. (2012) pointed out that CFD could be used to effectively model the flow fields of a non-Newtonian fluid in a constrained and swirling environment. They also concluded that the biogas yield in the lab-scale digester was neither impaired nor improved by changes in mixing speed for TS of 2.5%, and that mixing optimization should focus on the need to avoid grit deposition rather than optimizing mixing energy input from the perspective of optimizing biogas yield.

The rheological properties are important when designing and modeling manure flow. These properties have an obvious influence on the mixing time. The rheological behavior of liquid cattle manure has been studied by many researchers. Liquid manure is a non-Newtonian material and it behaves like a pseudoplastic liquid, which can be described using the power equation (Achkari–Begdouri and Goodrich, 1992; Landry et al., 2004; Wu and Chen, 2008).

Mixing time is defined as the time required for achieving a certain degree of homogeneity of injected tracer in a vessel (Harnby et al., 1997). The mixing time can be measured by experiment and numerical calculation. The experimental methods can be classified into non-intrusive and intrusive measurements based on the disturbance to flow, while they can be classified into direct and indirect measurements depending upon the type of data generated (Ascanio, 2015). Wu (2010) applied CFD to predict the mixing time in anaerobic digesters.

The objective of this research was to investigate the effect of mixing on biogas and methane production by comparing an AD experiment and numerical simulation using commercial CFD software Fluent 16.1. Four mixing intensities investigated were 50, 100, 150 rpm and non-mixed condition. The CFD technique was used to predict the flow fields and mixing time in the digester.

2. Materials and methods

Cattle manure used in this study was obtained from the Yangtze River Dairy Industry, Zhenjiang, China. The average dairy cow produced about 40 kg of milk a day. The fresh manure was collected from the transfer gutter close to the barn as a semi-solid and transported to the facility housing the pilot-scale digester. The manure was scraped frequently by an alley scraper and a gutter scraper, hence manure taken from the gutter was assumed to be only a day old. The fresh manure collected in multiple drums was stored in a cold storage water basin for at most two weeks. Daily, ice blocks were placed in the water basin to minimize fermentation during storage. The purpose was to keep the average daily temperature at 4 °C. The average daily temperature of the influent was about 8 °C which did not affect the daily methane production because of temperature shocks and slow methanogens growth. Samples were taken daily to determine the effect of storage on VS and the digestion processes.

2.1. Experimental set-up and apparatus

The pilot-scale digester with total volume of 1.63 m^3 was constructed by Zhenjiang Jianggong Biological Engineering Equipment Co., ltd. Fig. 1 shows a 2-dimensional sketch of pilot-scale stirred digester. Table 1 shows the geometry of pilot-scale stirred digester. The daily biogas production rate was recorded manually from a gas flow meter directly connected to the gas outlet. The methane concentration was measured using GASTIGER 2000 with a temperature and relative humidity compensation sensor by connecting it to the outlet of the gas flow meter. Gas was vented to maintain atmospheric pressure in the AD. Continuous measurement of the digester operating temperature and the pH were controlled by a computerized monitoring panel. Heating of the digester was automated and controlled by the computerized monitoring panel to regulate hot water from the water heater tank and cold-water entry into the insulated water jacket for keeping the set temperature. Samples of the digester content were taken from the side outlet daily for