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Dry fermentation of manure with straw in continuous plug flow reactor: Reactor development and process stability at different loading rates

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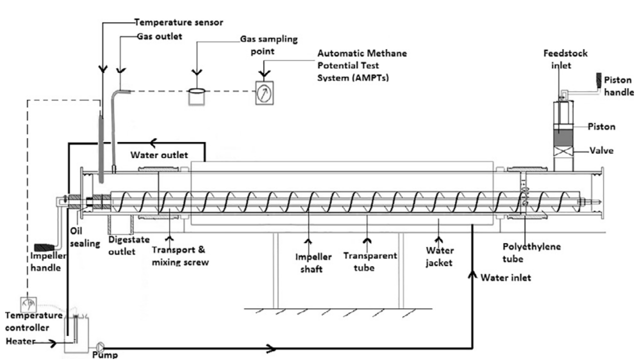
HIGHLIGHTS

- New plug flow reactor developed for continuous dry digestion processes.
- Reactor worked successfully for 230 days using untreated manure with straw at 22% TS.
- Methane yield of 56% of the theoretical value was obtained at OLR of 4.2 gVS/L/d.
- OLR of 6 gVS/L/d caused process instability with 41% VS removal efficiency.

GRAPHICAL ABSTRACT



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ABSTRACT

In this work, a plug flow reactor was developed for continuous dry digestion processes and its efficiency was investigated using untreated manure bedded with straw at 22% total solids content. This newly developed reactor worked successfully for 230 days at increasing organic loading rates of 2.8, 4.2 and 6 gVS/L/d and retention times of 60, 40 and 28 days, respectively. Organic loading rates up to 4.2 gVS/L/d gave a better process stability, with methane yields up to 0.163 $LCH_4/gVS_{added}/d$ which is 56% of the theoretical yield. Further increase of organic loading rate to 6 gVS/L/d caused process instability with lower volatile solid removal efficiency and cellulose degradation.

1. Introduction

Anaerobic digestion of organic wastes for biogas production has been successfully applied but there is a need for improved processes and design of less expensive reactors. In this vein the drive for dry anaerobic digestion processes is increasing both in research and the industry because of technical simplicity in design, together with low construction and operational costs (Karthikeyan & Visvanathan, 2013; Kothari et al., 2014). Dry anaerobic digestion technology is designed to process more organic wastes per reactor volume with total solids (TS) content greater than 20% (Demirer & Chen, 2008; Fernández et al., 2008) treating food wastes, manure bedded with straw, garden wastes and other high solid waste fractions. In comparison with the wet anaerobic digestion process, this process allows higher organic loading rates (OLR), less pretreatment and gives better economic feasibility (Karthikeyan & Visvanathan, 2013) since the reactor volume is minimized and it is easier to handle the digestate residue.

Animal wastes and crop residues are one of the most abundant waste fractions generated worldwide, the amount of manure

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bedded with straw produced increases daily as the number of housed dairy herd increases. Cattle manure bedded with straw usually have a TS greater than 20%, farmers can use low cost anaerobic digesters to convert these enormous waste streams to biogas, thereby improve water quality, reduce methane and nitrous oxide emissions and improve soil fertility. Dry anaerobic digestion is therefore a better option for processing these wastes. Since biogas production involves a complex biological process, monitoring of the process is essential to avoid process instability and failure of the digester (Drosg, 2013). For enhanced performance of dry anaerobic digestion processes, a suitable reactor is required; considering the substrate composition, amount of substrate to be treated, and process economy of the reactor.

Plug flow reactors have been reported to be efficient for dry anaerobic digestion processes. These reactors are inexpensive and easy to build which make them a suitable technology to improve the livelihoods of farmers (Lansing et al., 2010, 2008). Plug flow reactors have also been reported to have the highest success rate in the United States, where 42% out of the 242 anaerobic digesters operating at livestock farms in 2015 were plug flow designs (USEPA, 2016). Nevertheless, some shortcomings, such as lower mass transfer due to lack of mixing, thermal stratification and solid sedimentation problems have been reported (Lansing et al., 2010). These problems can be minimized by the use of impellers in plug flow reactors. The impellers allow minimal mixing for better performance in the reactors. In high solid digestion processes, however, continuous mixing have been reported to indicate unstable performance at high OLR and it was observed that the continuously mixed unstable reactor became stable when the mixing level was reduced (Stroot et al., 2001). Researchers have also investigated the effectiveness of plug flow reactors on manure and other substrates with solid content in the range of 11–14% TS (Adl et al., 2012; Cantrell et al., 2008). There have been studies on dry digestion of different substrates in batch reactors but little information is available on dry digestion in continuous plug flow reactors. The innovation of this paper in meeting this gap was the development of a novel type solid-state plug-flow laboratory reactor to treat substrates at higher TS levels, i.e. greater than 20%.

The efficiency of this reactor was then investigated in a continuous dry anaerobic digestion process treating manure bedded with straw at 22% TS content. The main objective was to identify the critical OLR, above which instability can occur in the reactor. The process was monitored by measuring VFA/Alkalinity ratio, pH, volatile fatty acid (VFA) and total ammonia nitrogen concentrations regularly. This is vital because the cost of starting the entire process over again far outweighs monitoring of the process.

2. Materials and methods

2.1. Reactor design

A horizontal plug flow reactor (Fig. 1) for continuous dry anaerobic digestion process was designed and made-up at the University of Borås, Sweden. This reactor has 9.2 L total volume, 1565 mm length and maximum inside pressure of 10 kPa. It was mounted on a base surface with which a clamp to the two edges of the reactor was associated for suspending the reactor. Mesophilic (37 °C) conditions were maintained by circulating water from a heater, a thermostatic water bath (GD 100, Grant instruments Ltd., Cambridgeshire, UK), through a water jacket (150 mm outer diameter with 4 mm wall thickness and capacity of 5 L) surrounding the reactor. The reactor was then shielded with a 10 mm thick-Styrofoam to avoid heat loss.

The reactor was sub-divided into 3 zones as follows. Inlet zone – this part was made of polyethylene material with sealed buffer system to avoid the release of gas and air entering the system. This part can be considered as an inactive zone in the inlet system. A shutoff valve was connected at the inlet with a piston rod (made gas tight by O-rings). The inlet storage volume is about 0.256 L with 0.0053 L of feedstock per rotation.

Main Zone – the main zone of the reactor was made of a Polymethylmethacrylate (PMMA) material with 110 mm outer diameter and 5 mm thickness for easy handling and to make the reactor transparent. An impeller, installed on a hexagonal shaft that runs through the reactor connected the inlet to the outlet. The hexagonal shaft had two oil seals that prevented leakage of materials and several O-rings making the different parts gas tight. The impeller allowed mixing of the feedstock at the bottom part of the inlet, and transported the materials very slowly towards the outlet taking several rotations: 100 cm^3 per rotation but it can also depend on the viscosity of feedstock and working volume of reactor.

Outlet zone – this part was also made of polyethylene material with an outlet pipe for the collection of the digestate residue. The material was transferred from inlet towards outlet at the end of the reactor by rotating of the impeller shaft; as a result the digested residue was discharged through the outlet pipe while new materials were added. The impeller handle was connected to the outlet for manual rotation. In this zone, the gas outlet was also connected where the daily volume of biogas produced was measured by the tipping device in the automated methane potential test system (AMPTs); meanwhile with an inserted thermocouple the temperature of the reactor was controlled.

Safety measures – a construction was made with a polyethylene material at the inlet and outlet with specific rubber connectors for sealing. If pressure inside the reactor would increase beyond 10 kPa due to blockage in the gas outlet or for any reason, this part of the reactor could open up avoiding an explosion. All interior parts were carefully selected in order to avoid any chemical reaction with the experimental materials as well as any corrosion during the test.

Fig. 1 shows a schematic diagram of the reactor and the experimental set up together with other accessories, such as heater and water bath for maintaining the temperature, sampling point for biogas composition analysis and the AMPTs system for measuring the biogas produced.

2.2. Substrates and inoculum

The substrate, cattle manure bedded with straw, was collected from a cattle farm outside Borås (Sweden) and used as feedstock for the continuous anaerobic digestion process. During the experimental period two different batches, with similar content of total solids (TS) and volatile solids (VS) were obtained from the same farm. The manure was shredded manually to reduce the particle size of straw; then it was characterized, weighted and stored in plastic containers at −20 °C to prevent biodegradation until further use. During experiment, weighted frozen substrate was defrosted at room temperature and thoroughly mixed to gain a homogenized feed before use. Sludge used as inoculum was obtained from a digester treating waste water sludge and operating at mesophilic conditions (Vatten and Miljö i Väst AB, Varberg, Sweden). The inoculum was filtered through a 2 mm porosity sieve to remove sand, plastic and other unwanted particles after which it was acclimated for five days in an incubator at 37 °C prior to use. The inoculum was centrifuged at 10,000g for 10 min to obtain a TS content of 7.8 ± 0.24%. Table 1 shows the most important characteristics of the substrate and the inoculum used during the investigations.

2.3. Experimental procedure

The substrate was inoculated with inoculum to start-up the reactor, keeping a volatile solids (VS) ratio ($VS_{substrate}$ to $VS_{inoculum}$)