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Measuring active volume using electrical resistance tomography in a gas-sparged model anaerobic digester

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ABSTRACT

Inadequate mixing in anaerobic digesters fitted with gas sparging systems is caused by many factors, and leads to dead zones where sludge remains stagnant. The present study explores a range of gas sparging configurations that can be implemented to maximize active volume, and validates electrical resistance tomography (ERT) as an effective measurement tool for analysing mixing conditions without the need for visual access to the liquid volume. Air was used as the gas phase, and xanthan gum Keltrol-T (XGKT) solutions at concentrations of 0.15 and 0.4 wt% were selected as transparent simulant fluids for their rheological similarity to digested sludge. Gas flow rate, sparger nozzle orientation (upward-facing vs. downward-facing), and nozzle height were varied, and mixing performance was assessed using flow visualisation experiments. Results were then replicated with ERT for comparison. It was found that the 0.15 wt% XGKT solution achieved almost complete mixing for all configurations, while the 0.4 wt% XGKT solution developed stable, unmixed regions. Gas flow rate made little difference to the final mixed volume suggesting lower power input does not sacrifice steady-state active volume in the reactor. Positioning the nozzle closer to the bottom of the vessel and sparging gas downward both reduced inactive volume. ERT measurements matched flow visualisation results closely, and were able to capture details that flow visualisation ignores. It has been shown that there is great potential for implementing ERT as a method for researching flow behaviours in complex opaque materials, especially the formation and progression of active volume.

1. Introduction

Anaerobic digestion is a core waste treatment process for converting organic effluent into useful end products such as methane rich biogas and odourless biosolids in an oxygen-free environment. It is applied to a wide range of feedstocks such as industrial and municipal wastewater, as well as solid waste from agriculture and the food industry. Rapidly expanding urbanisation has led to an increasing need for wastewater treatment plants to intensify existing processes with more concentrated feedstock in the form of thickened sludge. This has introduced a number of new engineering challenges, especially with respect to effective mixing to ensure homogeneous process conditions. Proper mixing helps to improve the temperature uniformity, distribute the substrate evenly throughout the digester volume, and minimise solids accumulation and scum.

The formation of dead zones has long been recognised as a critical problem for all digesters. Tenney and Budzin (1972) found that about half the primary digester volume was stagnant and unavailable for digestion in units they investigated. Monteith and Stephenson (1981) studied the mixing efficiencies of full-scale anaerobic digesters at two water pollution control plants in Ontario, showing that dead zones comprised 77% of the volume available for active mixing, and that 61% of the digester input was not treated properly due to short-circuiting. It is therefore imperative to understand and quantify the mixing level and

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Table 1 – Rheological properties of digested sludge and XGKT solutions.

Types of solution	Concentration (wt%)	Yield stress (Pa)	Flow behaviour index, n	Flow consistency index, k (Pa·s^n)
Digested sludge	2.23	0.497	0.538	0.214
XGKT solution	0.15	0.444	0.481	0.246
	0.4	1.648	0.421	0.733

flow behaviours inside digesters in order to handle the ever-increasing demands on treatment facilities.

Sludge is a non-Newtonian material with yield stress and shear thinning characteristics (Baudez and Coussot, 2001; Mori et al., 2006), and can be well described by the Herschel–Bulkley rheological model shown below:

$$\tau = \tau_y + K\dot{\gamma}^n$$

where τ is shear stress (Pa), τ_y is the fluid's yield stress (Pa), K is the consistency index, n is flow index, and $\dot{\gamma}$ is the shear rate (s^{-1}). The yield stress term indicates the minimum amount of stress required before the fluid will start flowing. This is important for sludge mixing, since any part of the liquid volume that does not have sufficient force exerted on it to overcome the material's yield stress will effectively remain locked in place and stagnate. Sludge experiences highest shear rates in the region near the mixing source, tapering off with distance from the power input location. Material will flow and mix in the volume up to a boundary where shear rates are low enough that the yield stress is not met, resulting in a distinct active region and an inactive region (Solomon et al., 1981).

There are several methods for mixing sludge in anaerobic digesters, one of the most prominent being biogas mixing systems. Gas is sparged into the liquid volume, and the rising bubbles induce flow by transferring momentum to the surrounding material (Dapelo et al., 2015), effectively turning the fluid over and circulating it through the tank. While these systems are broadly used in industry, the impact of factors such as sparger nozzle location and orientation, sludge viscosity, and power input on mixing effectiveness is poorly understood.

An important confounding factor for investigating sludge mixing is the material's opaqueness. Imaging flow patterns inside a volume of sludge with conventional tracer tests is impossible, since any substance placed in the vessel is completely obscured. The idea of using a simulant fluid which mimics sludge flow behaviour as an analogue material for digester mixing was introduced by Dawson et al. (2000), and several studies have since adopted the use of transparent liquids to infer sludge flow behaviour. Recording and analysing images of an optical tracer injected into a transparent simulant provides a robust indication of how fluid elements are transported through the liquid. Optimal sparger configurations, and the impact that variations in fluid rheology have on maximising active volume can be identified by analysing the spread of the tracer as mixing progresses. While this method has been successful in developing several models and predictions for digester mixing applications, it is difficult to say how closely the behaviour of real sludge is reflected by the relatively simple simulant fluids used. An imaging technique that does not rely on optical access to the fluid volume would allow direct experimentation with real sludge, and provide greater confidence in the accuracy of results.

Electrical resistance tomography (ERT) is a non-intrusive and robust measurement technique, which allows visualisation of mixing regions in opaque fluids. While transparent simulants have been shown to produce useful results, municipal sludge is a complex material with internal structures, suspended solids, and interactions that model liquids used in research are incapable of fully replicating (Naessens et al., 2012). Demonstrating that ERT can reliably produce accurate data for digester mixing will provide researchers with a powerful tool for directly observing sludge behaviour, rather than relying on inference based on simpler proxy fluids.

Although the problem of poor mixing in anaerobic digesters has been recognised for some time, there has been little progress in developing comprehensive models and solutions for improving process efficiency. Using a transparent simulant with rheological properties similar to digester sludge, this paper evaluates four fundamental sparger mixing system variables to determine optimal configuration for maximising active volume. These include differences in fluid rheology, gas flow rate, sparger nozzle orientation (upward facing vs. downward facing), and nozzle height from the bottom of the vessel. Observations of mixing patterns in real sludge will require non-visual imaging such as ERT. We seek to validate this tool by reproducing experimental results in a transparent simulant generated through established imaging techniques, and lay the groundwork for moving away from simple simulant fluids by developing methods for working with samples of the optically inaccessible sludge found in wastewater treatment plants.

2. Materials and methodology

2.1. Simulant selection and preparation

An aqueous solution of xanthan gum Keltrol-T (XGKT) was chosen as the model fluid in this work due to its yield stress, and shear-thinning rheological behaviour closely matching digested sludge in wastewater treatment plants. XGKT solutions are easy to prepare and handle, are transparent, stable within a wide range of pH, and are cost effective. Solutions were prepared by adding XGKT powder to deionised water and stirring by impeller at 400 rpm until completely dissolved. They were then left to stand overnight allowing time for trapped air bubbles to escape. Simulant fluids at concentrations of 0.15 and 0.4 wt% XGKT were used in this study to represent rheological properties of sludge samples taken directly from industrial digesters, as well as more viscous solutions in keeping with current trends toward increasingly concentrated feedstocks. Samples' flow behaviour was well described by the Herschel–Bulkley model, with rheological parameters summarised below (Table 1).

2.2. Gas sparging system

All experiments were conducted in a cylindrical vessel with a diameter (D_T) of 0.19 m. For flow visualisation experiments, this operating tank was placed in a second, cubical vessel filled with water to reduce optical distortion caused by the curvature of the first. Liquid height in the cylindrical tank was equal to the tank diameter in all experiments, giving an aspect ratio of 1:1.

Gas sparging was carried out with air as the gas phase and an XGKT solution as the liquid phase. The experimental arrangement used for gas sparging tests is shown in Fig. 1. Compressed air was delivered to the liquid volume through a 2 mm (internal diameter) metal tube. Two nozzle orientations were investigated in this work; downward facing (Fig. 1a), and upward facing (Fig. 1b), with nozzles located at mid-liquid height at the centre of the tank.

The air flow rate for a given run was based on the power input P (W), calculated using an equation suggested by Casey (1986):

$$P = \frac{\gamma \dot{Q}_{air} P_2}{(\gamma - 1)} \left[\left(\frac{P_1}{P_2} \right)^{\frac{(\gamma-1)}{\gamma}} - 1 \right]$$