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Flow patterns in the mixing of sludge simulant with jet recirculation system

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ABSTRACT

In this study, we examined the efficiency of mixing due to liquid jets in a model anaerobic digester. Xanthan Gum Keltrol T (XGKT) solution which is transparent and has similar rheological characteristics to those of digested sludge was selected as the model liquid. Experiments were carried out using 0.15 and 0.4 wt% XGKT solutions. Four different liquid jet orientations were used in a cylindrical vessel, namely vertical-downward, vertical-upward, tangential 45° upward and tangential 45° downward. A decolourisation method involving an acid–base reaction was used for flow visualisation. A fluorescent dye was used as the tracer to observe the mixing patterns in the vessel. Video images of flow visualisation experiments were analysed to investigate the changes in the volume of well-mixed regions as a function of mixing time. The results from flow visualization were compared with those from both computational flow dynamics (CFD) simulations and electrical resistance tomography (ERT). Results showed that well mixed region volume decreases with increasing liquid apparent viscosity. Complete mixing was achieved in 0.15 wt% XGKT solution, which has rheology similar to that of digested sludge with 2.3% solids, with all four different jet arrangements. For 0.4 wt% XGKT solution, which has rheology similar to that of digested sludge with 5% solids, mixing efficiency with jet arrangement changes in the following order: upward > 45° upward > 45° downward > downward jet arrangement. The results suggested that we can use transparent materials to study rheological behaviours of sludge and visualize the dynamics of mixing. Results from both ERT and CFD agreed well with those from flow visualization experiments.

1. Introduction

Anaerobic digestion is a unique process where organic wastes breakdown and convert into useful end products such as methane rich biogas and odour free biosolids. The potential of methane production from anaerobic digestion has brought up the attention in industries, as methane is a source of renewable energy, which can be used to generate energy for plant usage. Interest in energy-saving waste treatment has led to more investigations on anaerobic digestion in recent years (Farno et al., 2015, 2014; Liu et al., 2015; Fernández et al., 2014; Li et al., 2014; Markis et al., 2014; Eshtiaghi et al., 2013, 2012; Tauseef et al., 2013; Venkatesh and Elmi, 2013; Yu et al., 2013, 2011).

A key factor for the success of an anaerobic digester is mixing (Bhattacharjee et al., 2015; Subramanian et al., 2015; Dapelo et al., 2015; Hurtado et al., 2015; Lindmark et al., 2014; Subramanian and Pagilla, 2014; Wu, 2010; Terashima et al., 2009; Karim et al., 2007). Adequate digester mixing is required to allow a uniform dispersion of incoming substrate throughout the whole digester volume, to ensure homogeneity of temperature and pH, to minimise deposition of solids, and to prevent short-circuiting of digester feed sludge. According to Lusk (1998), most of the digesters in the USA were shut down for maintenance after operating for a short period.

The majority of the digester mixing studies was carried out using municipal sewage sludge or animal waste slurry (Stafford, 1982; Karim et al., 2004, 2005; Borole et al., 2006; Varma and Al-Dahhan, 2007). Real sludge is an opaque material and hence direct visualisation of the flow

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patterns cannot be implemented in anaerobic digesters. An alternative to study digester mixing is to conduct experimental work with a transparent model fluid, which has rheological properties similar to that of sludge. Flow patterns formed can then be easily observed using a non-intrusive flow visualisation method such as the one that involves acid–base reaction (Lamberto et al., 1996; Makino et al., 2001; Yek et al., 2009). This technique has been widely used in mixing studies for processing industries. Fundamental knowledge from those studies provides useful information to improve the design of mixing vessel configurations. Similarly, better understanding of flow structures inside digester can be helpful in improving mixing efficiency of anaerobic digester.

In addition to experimental investigations, digester mixing studies were carried out computationally (Vesvikar and Al-Dahhan, 2005; Karim et al., 2007; Mendoza et al., 2011). Veskikar and Al-Dahhan (2005) employed a three-dimensional steady state computational fluid dynamics (CFD) to simulate the flow structures and hydrodynamics parameters of the mimic anaerobic digesters. The CFD results were compared with the data obtained in experimental work which involved computer automated radioactive particle tracking (CARPT) and computed tomography (CT) techniques conducted by Karim et al. (2004). Overall, the simulations results agree reasonably well with the experimental outcomes. CFD is a valuable and efficient tool for the study of hydrodynamics in digester mixing. However, the closure equations and models for multiphase systems are not well developed. Thus, it is vital to validate the CFD results with the data obtained from experimental work for any multiphase flow system.

Electrical resistance tomography (ERT) is a non-intrusive and robust measurement technique which offers the opportunity to visualize the mixing of opaque fluids in a non-transparent vessel without disturbing the flow. ERT provides useful information such as concentration fields that allow the measurement of homogeneity and flow patterns inside the tank. Poor mixing regions in the opaque fluids can then be identified and eliminated. This technique has been used by many researchers to study the formation of caverns in the mixing of non-Newtonian fluids (Patel et al., 2013; Pakzad et al., 2008a,b).

In the present paper, flow visualisation technique has been used to study the formation and growth of active volume in a mimic lab-scale digester with a liquid recirculation (hydraulic mixing) system, which has not been reported previously in the literature. This paper evaluates the mixing performance of the mimic digester by changing specific power inputs and jet arrangements employed in the system. The results were compared with those from ERT and CFD simulation.

2. Experimental methods

2.1. *Rheology of digested sludge and simulant*

Understanding of digested sludge rheology is essential for digester mixing investigation. Digested sludge with 2.23 wt% solid concentration was collected from wastewater treatment plants for rheological measurements. Flow curve of digested sludge was measured at 37° C which is digester operating temperature. The procedure of rheological properties measurements of digested sludge was similar to that used by Eshtiaghi et al. (2012) in a sludge rheology study. Results from rheology tests are very useful in giving guidance and information on selecting a suitable model fluid to be employed in this study.

A transparent model fluid was used to substitute digested sludge as the working material in this study. Opaque nature of sludge has greatly constrained the visual observations of the flow structures formed during mixing. In this case, transparency of the simulant is necessary as it allows flow visualisation technique to be used in this study. In addition, model fluid must exhibit similar rheological characteristics as those of digested sludge. Thus, xanthan gum Keltrol T (XGKT) was selected to model the digested sludge in this study. In addition to similar rheological properties, XGKT solution is also cost effective and easy to prepare. It is a safer material for study purpose as compared to digested sludge which is biohazardous.

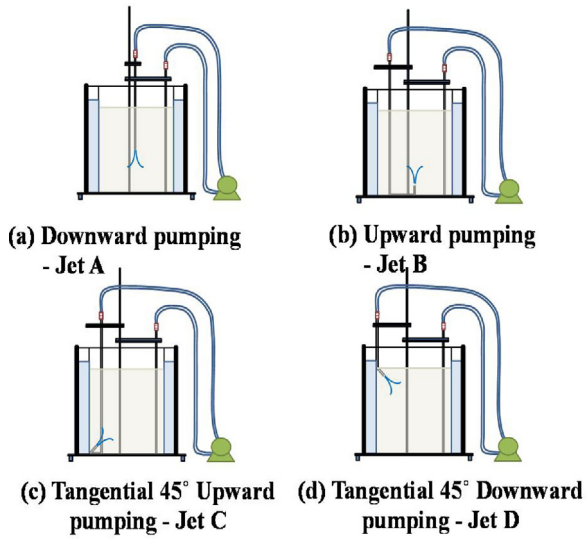

Fig. 1 – Schematic diagram of different nozzle arrangements in liquid recirculation system.

Rheological behaviour of XGKT solution was measured at 20° C and compared with the rheological properties of digested sludge at 37° C as published in Low et al. (2012). XGKT solutions with concentrations of 0.15 and 0.4 wt% were used. According to the previous work by Low et al. (2012), both 0.15 wt% XGKT solution and 2.23 wt% of digested sludge were having similar rheological behaviour. Hence, XGKT solution with 0.15 wt% concentration was chosen to be the model fluid for 2.23 wt% digested sludge whereas 0.4 wt% XGKT solution was representing digested sludge with a much higher solids concentration. XGKT solution is a shear-thinning fluid. Densities of 0.15 and 0.4 wt% XGKT solutions are 999 and 997 kg/m^3 respectively. Preparation of the XGKT solution was done as per the method described in Low et al. (2012).

2.2. *Experimental setup*

A laboratory scale cylindrical tank with a diameter of 19 cm was used in this study. The height of the liquid was kept at 19 cm resulting in a working solution volume of 5.39 l. The curved surface of the cylindrical vessel can cause visual distortions. Thus, the cylindrical tank was located inside a cubical tank, where the space between two tanks was filled with water to reduce optical distortions. This study involves liquid recirculation mixing where four different jet arrangements were installed individually in the system. They are vertical-downward, vertical-upward, tangential 45° upward and tangential 45° downward as shown in Fig. 1. Withdrawal point was fixed at the bottom right of the vessel. The diameters of injection and suction nozzles were 6 and 10 mm, respectively. A constant amount of XGKT solution was continuously withdrawn from the bottom of the vessel throughout the whole experiment. A peristaltic pump was used to pump and recirculate the withdrawn solution back into the mixing vessel via jet outlet oriented at different positions.

A range of specific power inputs (5–8 W/m^3) was recommended by U. S. EPA (1987) for anaerobic digester designs.