CHEMICAL ENGINEERING TRANSACTIONS

VOL. 29, 2012

Guest Editors: Petar Sabev Varbanov, Hon Loong Lam, Jiří Jaromír Klemeš
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ISBN 978-88-95608-20-4; **ISSN** 1974-9791

A publication of
AIDIC
The Italian Association
of Chemical Engineering
Online at: www.aidic.it/cet

DOI: 10.3303/CET1229221

Hydrodynamics Study of Sludge in Anaerobic Digesters

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Inadequate design and improper mixing operation in anaerobic digesters often lead to poor mixing and digester failures due to the presence of dead zones formed in the digester. More research is required to understand the mixing phenomena in anaerobic digesters and thus improve their efficiency. This paper investigates the efficiency of mixing of digester sludge in a mechanically agitated vessel. A transparent model fluid (Xanthan Gum Keltrol T – XGKT) was used as a model fluid. Four different concentrations of XGKT solutions (0.15, 0.225, 0.3 and 0.4 wt%) were studied as they exhibits similar rheological characteristics of digested sludge with different solids concentration. Experiments were conducted using a standard six-bladed Rushton turbine in an unbaffled mixing vessel. Direct visualization of an acid-base neutralization reaction with fluorescent green dye was used to measure the mixing time. Changes in volume of unmixed flow elements i.e. 'isolated mixing regions' (IMRs) and well mixed flow elements i.e. caverns were studied by carrying out image analysis. Results showed that active volume decreases with increasing liquid viscosity at higher Xanthan Gum concentrations. In 0.15 wt% solution, IMRs are found above and below the impeller. With increase in mixing time, the IMRs destroyed continuously until disappeared. For 0.225, 0.3 and 0.4 wt% solutions, caverns were found around the impeller. With increasing mixing time, cavern grows and reaches a constant value. Homogenous mixing cannot be achieved with sludge, whose rheology is similar to that of 0.225, 0.3 or 0.4 wt% solutions, even after a long mixing period.

1. Introduction

Anaerobic digestion is a biological conversion of organic waste into useful end products such as methane rich biogas and odour free biosolids. Methane is a cleaner energy source and thus this has raised the interest of researchers to improve the efficiency of anaerobic digestion for increasing the rate of production of biogas.

Mixing in in digesters is commonly achieved via mechanical stirring, liquid recirculation and gas recirculation. Good mixing can provide a good contact between the active biomass and feed sludge, maximise the biogas production, prevent solid deposition, and minimise sludge short-circuiting. Uniformity of the temperature and solids concentration can also be achieved with adequate mixing. Temperature and concentration uniformity is essential for the bacterial activity in digesters. In contrary, poor design and improper mixing often lead to poor mixing and digester failures due to the presence of dead zones. Therefore, the operational efficiency of anaerobic digesters ultimately depends on the hydrodynamics produced by mixing.

Many papers in the literature have highlighted the problems encountered in industrial digesters. Tenney and Budzin (1972) examined the residence time distribution of tracers in anaerobic digesters by injecting fluoride tracer. They showed that about half of the digester volume was stagnant. They have suggested that process parameters have to be over-specified to compensate for the inefficiency in mixing. Formation of stagnant regions in digesters was also reported by Monteith and Stephenson

Please cite this article as: Low S. C., Parthasarathy R., Slatter P. and Eshtiaghi N., (2012), Hydrodynamics study of sludge in anaerobic digesters, Chemical Engineering Transactions, 29, 1321-1326

(1981). They investigated the mixing efficiencies of full-scale anaerobic digesters at two water pollution control plants in Ontario. In addition to the dead zone formation, they also reported that short-circuiting was a significant issue in anaerobic digesters. Typically in primary digestion tanks, they showed that dead zones comprised of 77 % of the volume available for active mixing and 61% of the digester input did not get treated properly due to short-circuiting. Moreover, a review from the Department of Energy, USA on large anaerobic digesters in farm operations showed that the failure rate of digesters was 50% overall (Borole et al., 2006). These findings indicate that a better understanding on digester mixing is necessary to improve the effective mixing in anaerobic digestion.

According to Dawson et al. (2000), there is no definitive mixing theory for digester design. Digesters are usually designed based on the experience of manufacturers, operators and design engineers. Developing a universal digester mixing theory is very challenging as the sludge composition and rheology, and the mixing system used in digesters vary from site to site. Fundamental knowledge on digester mixing including the effect of process parameters on digester performance is required to develop such theory. To date, limited design information is available on digester mixing. Many digester mixing systems were generally designed based on two quantified design guidelines in the literature provided by U. S. Environmental Protection Agency (EPA) (1987) and Degremont (2007). Unfortunately, sludge rheology and digester geometries were not considered in these design guidelines. Inconsistent outcomes are obtained when using different design guidelines for scaling or changing aspect ratio or using different types of mixing system in digesters. This can lead to improper digester design which may not meet the requirements of the industry. Barker and Dawson (1998) reported based on a site survey that the mixing systems in operational digesters were underdesigned compared to EPA guideline values.

The importance of mixing in achieving an efficient substrate conversion has been reported in the literature (Casey, 1986; Lee et al., 1995; Smith et al., 1996). However, there is no consistent information in the literature on the mixing intensity required to achieve efficient substrate conversion. Thus, more studies are required on digester mixing to determine the optimum mixing intensity. Degree of mixing is closely related to the hydrodynamics inside digester. So, it is important to understand the sludge mixing characteristics for each mixing mode used in digesters and thus improve digester efficiency. This paper aims to study the mixing performance of a digester equipped with a mechanical impeller and determine the optimum impeller power input for digested sludge mixing. Sludge rheology is taken into account in determining the mixing efficiency.

2. Experimental Methods

2.1 Digested Sludge and Simulant Rheology Measurements

Digested sludge was commonly used in digester mixing studies reported in the literature. However, fluid flow occurring inside the digester cannot be visualized because sludge is opaque. In this study, a transparent model fluid, Xanthan gum Keltrol T (XGKT), was selected to represent digested sludge as the working fluid in experiments.

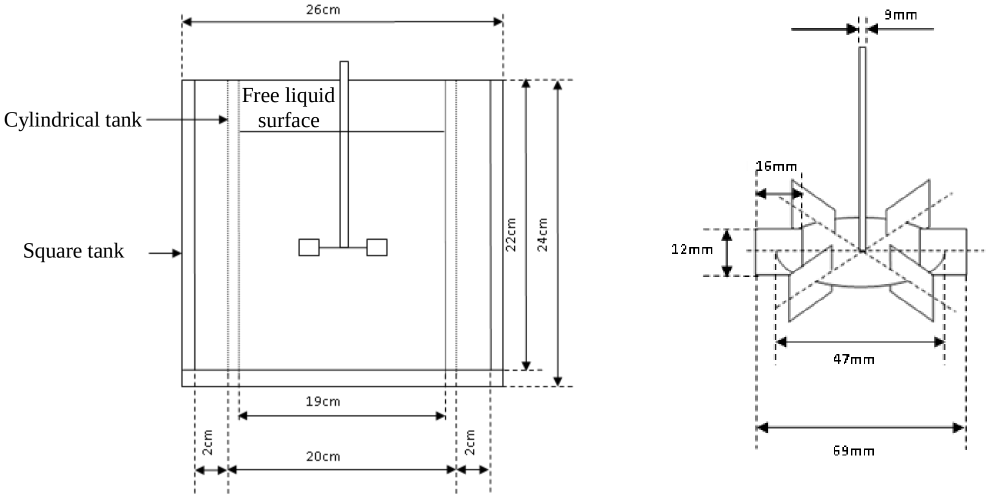
Samples of digested sludge collected from municipal wastewater treatment plants contained 2.23 wt% solids. Rheological characterisation of digested sludge was carried out at the digester operating temperature of 37 °C. Eshtiaghi et *al*., (2012) used similar procedure to study sludge rheology.

Model fluid used in this study (XGKT solution) is a shear-thinning fluid and its density at various concentrations ranged from 997 to 999 kg/m^3. All experiments were conducted at 20 °C. Therefore, rheological properties of XGKT solution were also determined at 20 °C and compared with those of digested sludge.

2.2 Experimental setup

XGKT solutions with four concentrations (0.15, 0.225, 0.3 and 0.4 wt%) were investigated in this study. XGKT solution was prepared in a cylindrical vessel by mixing the required amount of XGKT powder with deionised water. The solution was left to stand unstirred for 24 hours to allow the trapped air bubbles to escape. All experiments were carried out in a laboratory scale cylindrical vessel with a diameter of T = 19 cm, equipped with a six-bladed Rushton turbine at the axis of the tank (Figure 1a). The details of the impeller used are shown in Figure 1b. The cylindrical tank was located inside a

square tank and the gap between the two tanks was filled with water. This is to eliminate the optical distortions caused by the curved surface of cylindrical vessel. The impeller speed was determined from the electric motor display and impeller power input was determined by measuring torque experienced by the impeller shaft using a torque transducer attached to the shaft. A specific power input range of 5 – 8 W/m^3 is recommended by U. S. EPA (1987) for anaerobic digesters operation. Impeller specific power input values in this range were chosen for this study. Details of the XGKT solution concentration, temperature, and specific power input values used in the experiments are shown in
Table 1.



(a) (b)

Figure 1: Schematic diagram of (a) mixing tank and (b) impeller - 6-bladed Rushton turbine

Table 1: Experiment conditions for four different concentrations of XGKT solutions

No.	XGKT Concentration (wt%)	Temperature (˚C)	Specific power input (W/m^3)
1	0.150	20	5.5 and 7.7
2	0.225	20	5.0 and 7.7
3	0.300	20	5.3 and 7.8
4	0.400	20	5.5 and 8.0

Direct visualization of an acid-base neutralisation reaction was used to observe the flow patterns in the vessel during mixing. This method has been used in process mixing studies by many researchers (Lamberto, D. J. et al., 1996; Makino, T. et al., 2001; Yek, W. M. et al., 2009). Fluorescent green dye added to the XGKT solution acted as a passive tracer. XGKT solution was first made basic by adding NaOH solution and stirred until a steady pH is achieved. To maintain the working fluid at a constant 20°C, the water in the jacket was maintained at 20°C by circulating it through a constant temperature water bath. An acidic (HCl) solution was then injected into the tank at an axial location midway between the liquid surface and the impeller near the impeller shaft. The whole process during mixing was recorded at different intervals using a digital video camera.

Green dye started to disappear immediately after the injection of acid solution into the base solution. Inactive mixing regions appeared as green regions in the solution. To create a 2-dimensional (2D) view of mixing patterns, a light sheet was produced using two lamps placed on the opposite sides of the tank. The outer tank wall (except the front wall) was covered by cardboard to block the light going through the tank. Narrow vertical slits on the opposite sides of the cardboard allowed the light from the lamps to travel through the tank at its axis forming a square light sheet. The digital video camera was placed perpendicular to the sheet of light to record the 2D images of the mixing patterns. Digital image analysis was used to determine the cross sectional area of inactive regions, whereas decolourisation time was determined from the digitised time frames of the recorded video.

3. Result and Discussion

3.1 Comparison between digested sludge and simulant

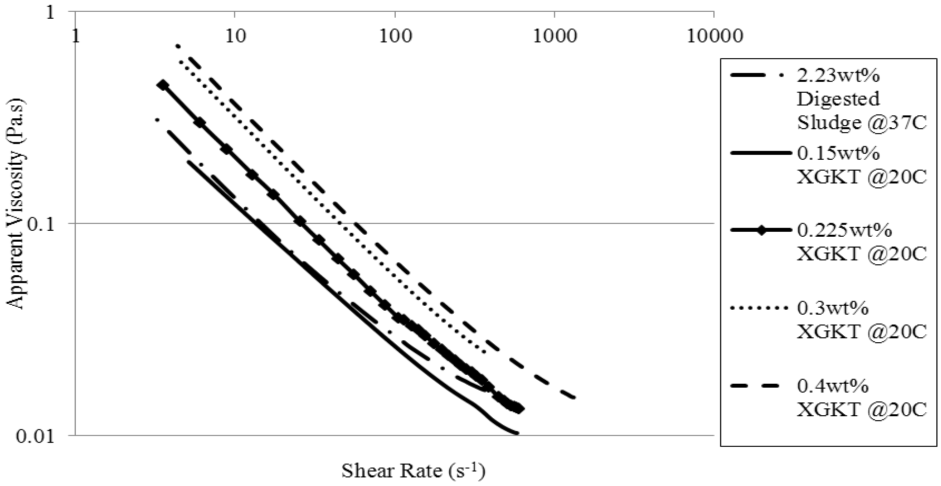


Figure 2: Comparison of apparent viscosities of 2.23 wt% digested sludge with those of 0.15, 0.225, 0.3 and 0.4 wt% XGKT solutions.

Rheological characteristics of digested sludge and XGKT solutions of four different concentrations were investigated in this study. Figure 2 shows the apparent viscosities of the sludge sample and XGKT solutions. It can be seen that the rheological characteristics of 0.15 wt% XGKT solution are similar to those of the sludge as the curves for these two fluids are very close to each other. Based on this observation, 0.15 wt% XGKT solution was chosen to be the simulant of the digested sludge whereas 0.225, 0.3 and 0.4 wt% XGKT solutions were chosen to represent the behaviour of digested sludge with higher concentrations.

3.2 Destruction of inactive volume in mechanical mixing system

Specific power inputs within the recommended range of 5 - 8 W/m^3 were used for mechanical mixing in this study. For a given specific impeller power input, mixing pattern observed for 0.15 wt% of XGKT solution was different from those observed in solutions with higher XGKT concentrations. It can be seen from Figure 3(a) that a ring shaped non-mixed region known as 'isolated mixing regions (IMRs)' appears above and below the stirrer in 0.15 wt% XGKT solution whereas a well-mixed regions known as 'cavern' is formed around the impeller in 0.225, 0.3 and 0.4 wt% XGKT solutions (Figure 3b).

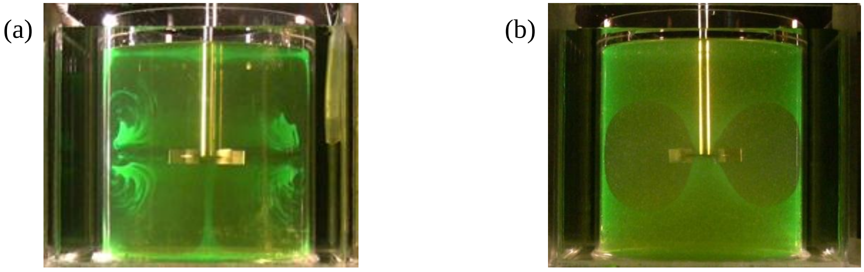


Figure 3: Inactive regions are shown as green regions whereas active mixing regions are the darker regions: (a) IMR structures (b) cavern.

These differences in mixing patterns led to different trends in the destruction of inactive regions. It can be seen from Figures 4a to 4d where the volume of inactive regions at different intervals is expressed as a percentage of total liquid volume in the tank as a function of number of impeller rotations (Nt_m). The inactive volume was determined by subtracting the mixed (active) volume from the total liquid volume.

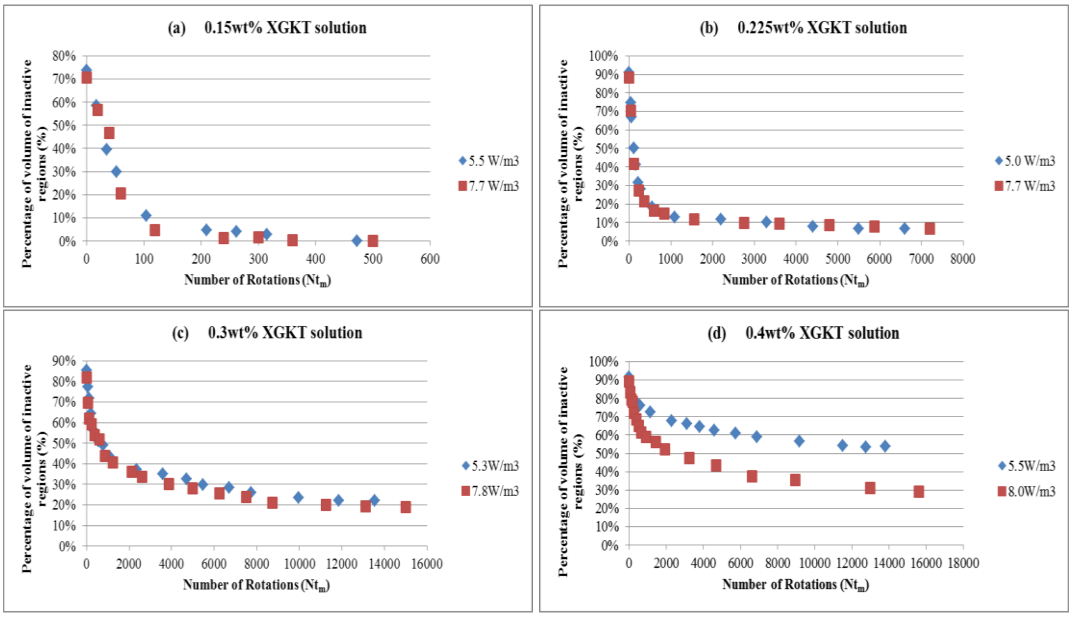


Figure 4: Reduction of inactive region as a function of number of impeller rotations at different power inputs: (a) 0.15 wt%, (b) 0.225 wt%, (c) 0.3 wt% and (d) 0.4 wt%.

For 0.15 wt% XGKT solution, IMRs occupy nearly 3/4th of the tank volume initially (Figure 4a). As mixing proceeds, the total volume of IMRs decreases and becomes zero. All dead regions are destroyed and complete mixing is achieved for specific power inputs of 5.5 and 7.7 W/m^3. It takes about 480 impeller rotations for the inactive volume to be destroyed completely for these specific power inputs. There is no significant difference in the mixing performance for both power inputs as the IMRs are reduced nearly at the same rates.

In the case of solutions with 0.225, 0.3 and 0.4 wt% XGKT concentration, homogeneous mixing cannot be achieved with the specific power inputs used. Inactive regions are not completely destroyed in all these solutions. In the case of solutions with 0.225, and 0.3 wt% XGKT concentration, the rate of dead zone reduction is the same for specific power inputs of 5.0 and 7.7 W/m^3 (Figures 4b and 4c). The total volume of dead zones decreases gradually with increasing number of rotations and reaches a plateau. The changes in the cavern size with increase in number of impeller rotations are found to be minimal after 1000 and 10000 of rotations for 0.225 and 0.3 wt% XGKT solutions, respectively. In the case of 0.4 wt% XGKT solution, about 10% of the total liquid volume is occupied by the cavern initially. The cavern size increases with increase in number of impeller rotations but at a much slower rate. Even after 16000 rotations, the liquid volumes that remain unmixed are 50 and 29% for specific power inputs of 5.5 and 8.0 W/m^3, respectively.

Overall, it is clear that using adequate specific power input is important for mixing solutions with higher XGKT concentrations. Inadequate power input can lead to poor mixing where large inactive regions could remain undestroyed even after long mixing time. In addition, using a specific impeller power input higher than that required will not further improve the rate of dead zone destruction. In other words, using a specific power input higher than that required will be a waste of energy.

4. Conclusion

This paper demonstrated that consideration of sludge rheology is important in the study of digester mixing. Xanthan Gum Keltrol T - XGKT solution was chosen as the model fluid to represent digested sludge in this mixing study as it possessed rheological behaviour similar to that of digested sludge. XGKT solutions with different concentrations were used in this study. For a given specific power input, different mixing patterns were observed in XGKT solutions with different concentrations. Homogeneous mixing cannot be achieved in thicker solutions when operating under specific power inputs recommended in guidelines. Higher yield stress in thicker XGKT solutions lead to the formation of larger dead zones and they remain undisturbed even after long mixing time. These results suggest that poor mixing performance will result in digesters handling thickened sludge. Threshold power input required to achieve an optimum mixing varies with the concentrations of model solution used. Thicker solution will need higher threshold power input and vice versa. This is a result of the rheological characteristics of thicker XGKT solutions compared to thinner ones. Hence, sludge rheology needs to be considered in the design of digester mixing system to achieve optimum mixing.

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