Velocity gradient as a tool to characterise the link between mixing and biogas production in anaerobic waste digesters

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ABSTRACT

Whilst the importance of mixing in anaerobic digesters to enhance process performance and gas production is well recognised, the specific effects of mixing regime on biogas production are not clear. Here, the velocity gradient is used to demonstrate the importance of minimally mixed zones in a digester, with computational fluid dynamics (CFD) models indicating that 20–85% of a laboratory-scale digester experiences local velocity gradients of less than 10 $s^{-1}$, dependent on mixing speed. Experimental results indicate that there is a threshold above which increased mixing speed (and hence velocity gradient) becomes counter-productive and biogas production falls. The effects of minimal mixing on digester microbiology are considered with the creation or destruction of localised pockets of high acetate concentration providing a possible explanation for the velocity gradient threshold. The identification of this threshold represents a valuable contribution to the understanding of the effects of mixing on gas production in anaerobic digesters.

Key words | anaerobic digestion, biogas, CFD, mechanical mixing, velocity gradient

INTRODUCTION

Anaerobic digestion (AD) has been used as a stabilisation process for sewage sludge for over 100 years (Braber 1995). Sixty percent of the biogas produced by AD in the UK water industry is used to generate renewable heat and power in combined heat and power units. This makes up a large percentage of the 665 GWh of renewable electricity generated by the UK water industry in 2009–10 and accounts for 7.3% of the total energy used by the industry (Water UK 2010).

Mixing in anaerobic digesters is necessary to bring microorganisms in the biomass and food sources in the sludge together so that sludge stabilisation can occur. Furthermore, mixing promotes the establishment of a homogeneous environment by reducing temperature, pH, and concentration gradients within the reactor (Appels et al. 2008).

Although the importance of mixing for achieving optimum process performance and gas production is well recognised (Appels et al. 2008), there is no clear consensus as to what constitutes an optimal mixing regime. In order to design the optimal mixing regime for a given digester, it is necessary to determine to what extent biogas production is dependent upon the flow patterns in the digester, and how these flow patterns depend upon the mixing regime, the physical characteristics of the sludge and the digester configuration.

This paper considers the velocity gradient as a tool to demonstrate the importance of zones of minimal mixing in a digester on biogas production. In order to achieve this, computational fluid dynamics (CFD) models were used to calculate local velocity gradients in laboratory-scale digesters at a range of mixing speeds. These models mimicked experimental work undertaken to determine the change in biogas production from laboratory-scale, mechanically-mixed anaerobic digesters when the mixing speed was altered. The experimental results were considered in conjunction with the results of the CFD models to demonstrate the importance of pockets in the digester which experience low velocity gradients. The intermediary link between mixing and microbiology was then considered in order to provide a potential explanation for the findings of this research. This work represents a valuable contribution to the understanding of the effects of mixing on gas production from anaerobic digesters.

doi: 10.2166/wst.2013.206
METHODS

Velocity gradient

Camp & Stein (1943) considered the angular distortion of an elemental volume of water arising from the application of tangential surface forces and defined \( G \) as the root mean square velocity gradient in a mixing vessel, expressed algebraically as:

\[
G = \sqrt{\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2}
\]  

(1)

where \( u, v \) and \( w \) are velocity components in the \( x, y \) and \( z \) directions of a Cartesian coordinate system. This absolute velocity gradient is related to the work done per unit volume per unit time by:

\[
\Phi = \mu \left[ \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)^2 + \left(\frac{\partial u}{\partial z} + \frac{\partial w}{\partial x}\right)^2 + \left(\frac{\partial v}{\partial z} + \frac{\partial w}{\partial y}\right)^2 \right] = \mu G^2
\]  

(2)

where \( \Phi \) is power dissipation, equal to the total work done by shear per unit volume per unit time.

From this,

\[
\overline{G} = \sqrt{\frac{\Phi}{\mu V}} = \sqrt{\frac{P}{\mu V}} = \sqrt{\frac{\varepsilon}{v}}
\]  

(3)

where \( \mu \) is dynamic viscosity, \( P \) is the power of mixing input to the vessel, \( V \) is the volume, \( \varepsilon \) is energy dissipation per unit mass and \( v \) is the kinematic viscosity of the fluid.

In theory, the absolute velocity gradient, \( G \), can be calculated at any point within a mixing vessel, provided that the energy dissipation at that point is known. In practice, energy dissipation, along with other flow characteristics, varies across the vessel, making velocity gradient a function of time and location. Given these complications, the average velocity gradient throughout the vessel, \( \overline{G} \), is often approximated as:

\[
\overline{G} = \sqrt{\frac{P_{\text{ave}}}{\mu V}}
\]  

(4)

where \( \overline{G} \) is the average velocity gradient and \( P_{\text{ave}} \) is the average mixing power input to the vessel.

Camp and Stein originally applied the concept of the \( G \) value to the design and analysis of mixing, coagulation and sedimentation processes but since its introduction it has found use describing mixing in a wide range of engineering applications (Metcalf & Eddy 2003; Crittenden et al. 2005).

The value of \( \overline{G} \) is often used in the design of mixing vessels. However, it has been argued that the concept of \( \overline{G} \) is flawed as it attempts to represent a complex flow field with a single number (Clark 1985; Luo 1997). Neither the distribution of velocity gradients nor the distribution of power inputs within a digester is uniform, as areas of high power input (e.g. close to impeller), are likely to experience high turbulence and hence, velocity gradients several orders of magnitude greater than areas of low turbulence. As such, although a useful parameter to approximate overall conditions, the average velocity gradient does not sufficiently describe the fluctuations in local velocity gradient within a vessel. Nonetheless, CFD models of a digester can be used to determine the local values of velocity gradient and consider the range of local velocity gradients that are experienced across the reactor. It is these local variations that occur down to the Kolmogorov scale which can have an effect on individual micro-organisms and thereby determine the effect of mixing on gas production at a local scale within the digester.

CFD simulations

The mechanical mixing of an anaerobic digester is governed by continuity, momentum and turbulence equations. Furthermore, the nature of the flow is subject to the physical properties of the sludge.

In order to determine the range of local velocity gradients present in the laboratory-scale anaerobic digesters, commercial CFD software, ANSYS Fluent 13.0 (ANSYS-Fluent 2010) was used to create a multiple reference frame (MRF) three-dimensional CFD model of the digester. In the MRF approach, the area around the impellers is considered as a rotating zone, as shown in Figure 1(a), and the continuity and momentum equations are solved using a rotating reference frame, whilst for the rest of the digester (considered as stationary) the equations for a stationary reference frame are used. The solution is coupled at the interface between the rotating and stationary zones via velocity transformation from one frame to the other. The continuity equation in the rotating reference frame is expressed as:

\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0
\]

(5)
where $t$ is time, $\rho$ is fluid density, $\vec{v}_r$ is relative velocity vector in the rotating frame, calculated from the stationary frame as:

$$\vec{v}_r = \vec{v} - (\vec{\omega} \times \vec{r})$$

(6)

where $\vec{v}$ is the absolute velocity vector, $\vec{\omega}$ is the angular velocity vector and $\vec{r}$ is the position vector in the rotating frame.

The momentum in the rotating reference frame is expressed as:

$$\frac{\partial}{\partial t} (\rho \vec{v}) + \nabla \cdot (\rho \vec{v} \vec{v}) + \rho (\vec{\omega} \times \vec{v}) = -\nabla p + \nabla \cdot \vec{\tau} + \vec{F}$$

(7)

where $p$ is static pressure, $\vec{\tau}$ is viscous stress, $\vec{F}$ is body force and the Coriolis and centripetal accelerations are included in $(\vec{\omega} \times \vec{v})$.

The non-Newtonian fluid model used was calculated from viscosity measurements of the sludge used in the experimental work, carried out using a Couette viscometer (Fann Model 35). The model uses a density of 965 kg/m$^3$ and follows a non-Newtonian power law model, $\eta = k\gamma^n$, with consistency index, $k = 0.0788$ Pa·s$^{0.8088}$, power law index, $n = 0.8088$ and allowable viscosity range of 0.02–0.035 kg/m·s. A non-Newtonian power law viscosity model was chosen as it has been successfully employed to describe the rheological properties of sewage sludge previously (Seyssiecq et al. 2003) and is considered to be a robust but straightforward model. The turbulence model used was the realisable $k$-$\varepsilon$ model as it has been found to produce results that are comparable to those produced by the Reynolds Stresses Model (RSM) but is computationally less expensive (Wu 2011).

The CFD model of the laboratory-scale digester is of a cylindrical vessel (diameter = 0.2 m, height = 0.18 m) with a flat four-bladed impeller (diameter = 0.05 m, mixing speeds = 50, 100, 200 rpm) and four baffles (width = 0.02 m) spaced equally around the vessel wall. The mesh consists of 420,000 mesh cells with a maximum cell width of $2.5 \times 10^{-3}$ m as shown in Figure 1(b). Convergence criteria for $u$, $v$, $w$, $k$ and $\varepsilon$ were set at $1 \times 10^{-5}$. The local velocity gradient (calculated as $\sqrt{\varepsilon / \nu}$) at each grid cell was then calculated.

**Experimental set-up**

In order to assess the effects of different velocity gradient values on biogas production, three 6-l, baffled, mechanically-mixed digesters (sized as the laboratory-scale CFD model discussed above) were run at 35°C and at a constant mixing speed of 100 rpm until they achieved stability (considered to be achieved when they had a total alkalinity of 3,500–4,500 mg/l, pH of 7.5–8.0 and a volatile solids reduction of at least 75%). The mixing speeds in the digesters were then changed to 0, 50 and 200 rpm. The digesters were operated for a further three retention times or until failure, whichever occurred first. The digesters were fed with 250 ml of synthetic digester feed five times per week (Monday–Friday). A synthetic sludge was used here in order to minimise the impact of variation in the feed over time on the biogas production of the digesters. Feed composition is shown in Table 1 and is based on Carliell-Marquet (2000).
Throughout the duration of the experiment, biogas production was recorded using a tipping-bucket mechanism. The biogas production of the laboratory-scale digesters was then considered in conjunction with the local velocity gradients calculated by the CFD models to determine the effect of mixing on biogas production.

## RESULTS AND DISCUSSION

### Velocity gradient in laboratory-scale digesters

Histograms of the velocity gradients in the laboratory-scale digester, calculated from the CFD model, at different mixing speeds are shown in Figure 2. It can be seen that whilst there are small volumes of the digester that experience velocity gradients up to 100 s⁻¹, at all three mixing speeds, the majority of the digester experiences local velocity gradients in the range of 0–20 s⁻¹. Unsurprisingly, as the mixing speed in the digester is increased, there is a decrease in the very low velocity gradients and an increase in the volume of the digester that experiences higher velocity gradients.

As the mixing speed used in the digester increases, the percentage of high velocity gradients increases. However, even at 200 rpm, velocity gradients of less than 10 s⁻¹ still account for approximately 20% of the volume of the digester, suggesting that in a 6-l vessel mixed at a rotational velocity of 200 rpm, there are still significant pockets of

<table>
<thead>
<tr>
<th>Feed constituent</th>
<th>Concentration (g/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn flour (carbohydrate source)</td>
<td>6.3</td>
</tr>
<tr>
<td>Toilet paper (carbohydrate source)</td>
<td>9</td>
</tr>
<tr>
<td>Coffee creamer (fat and glucose source)</td>
<td>9.9</td>
</tr>
<tr>
<td>Bran flakes (fibre/lignin and carbohydrate source)</td>
<td>10.8</td>
</tr>
<tr>
<td>Yeast extract (protein source)</td>
<td>3.6</td>
</tr>
<tr>
<td>Sodium bicarbonate</td>
<td>5.4</td>
</tr>
<tr>
<td>Carboxymethyl cellulose (CMC)</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Table 1 | Composition of synthetic digester sludge

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Figure 2 | Histograms showing local velocity gradients for a laboratory-scale digester modelled with mixing at (a) 50 rpm, (b) 100 rpm and (c) 200 rpm.
fluid which experience little to no real mixing, despite the presence of baffles. These occur in the bulk of the fluid above and below the impeller, with the pockets of highest velocity gradient existing around the impeller region and close to the walls and baffles.

**Effect of mixing speed on biogas production**

The volume of biogas produced by each of the digesters in the second retention time after the change in mixing speed was compared to the volume of biogas produced by the same digester in the retention time prior to the change of mixing speed. This allowed one retention time after the change in mixing speed for the micro-organisms in the digester to acclimate. A daily gas volume from each digester was calculated for each retention time in order to take into account variations in the exact length of the period due to an incomplete gas volume record. The percentage increase or decrease in gas production was plotted against \( \bar{G} \) for the digester, calculated from the CFD models, and these results are shown in Figure 3.

It can be seen that, after the change in mixing speed, the digester at 50 rpm (\( \bar{G} = 7.2 \text{ s}^{-1} \)) experienced an increase in gas production of approximately 20%. In all of the other digesters, the gas production fell, with the digesters changed to no mixing and 200 rpm experiencing falls of approximately 18 and 56% respectively. These results suggest that a low mixing speed is preferable for maximising biogas production from a digester. Whilst it is well-known that mixing is required for feed sludge to come into close contact with micro-organisms in a digester allowing biogas formation, from these results, it is evident that there is a threshold above which increased mixing becomes counter-productive and biogas production falls. In the case of these laboratory-scale digesters, this threshold occurs between 7.2 and 14.3 \text{ s}^{-1}, within the shaded area in Figure 3. It is in this band of velocity gradients that a significant drop in the biogas production of the digester occurs, suggesting that damage to the microbiological environment of the digester takes place within this range. This threshold is far lower than the typical design parameter of \( \bar{G} = 50-80 \text{ s}^{-1} \) stated previously in the literature (Tchobanoglous & Burton 1991), although it is noted that Tchobanoglous and Burton provide no justification for their stated range. The results of this work suggest that \( \bar{G} \) values a degree of magnitude lower are more suitable to promote biogas production.

**Linking microbiology to mixing**

Having ascertained that significant areas of a digester experience minimal mixing, the effects of this on the microbiology of a digester were subsequently considered. The final stage of the AD process, methanogenesis, converts hydrogen and carbon dioxide, acetate, methanol and formate into methane and is the slowest stage of the process once the sludge has been hydrolysed. As the rate-limiting step in producing methane-rich biogas, it is this step that forms the focus of the analysis of the effects of mixing on microbiology.

Methanogens can be split into two main groups: acetoclastic methanogens which convert acetate to methane and hydrogenotrophic methanogens which convert hydrogen and carbon dioxide to methane (Griffin et al. 1998). Nearly all known methanogens are capable of converting hydrogen and carbon dioxide into methane, whilst very few known methanogens are capable of the conversion of acetate to methane. The only known acetoclastic methanogenic strains are *Methanosarcina* spp. and *Methanosaeta* spp., and research has shown that, due to the high concentrations of acetate found in anaerobic sludge (range of 50–900 mg l\(^{-1}\) across 30 digesters in the USA as given in Speece (1988)), they are responsible for approximately 70% of all methane production in domestic sludge digestion (FAO 1997). *Methanosarcina* has a greater maximum rate of acetate utilisation and maximum growth rate, a greater half-saturation coefficient and a greater yield coefficient compared to *Methanosaeta* (Conklin et al. 2006). This would suggest that *Methanosaeta* will dominate when acetate concentrations are low or when solid retention times (SRT) are high, with *Methanosarcina* dominating when the reverse is true.

In most cases, *Methanosaeta* is the dominant acetoclastic methanogen in anaerobic digesters (Conklin et al. 2006). However, in rapid start-up reactors which have very high
acetate levels (peaking at 66–83 mmol l\(^{-1}\) acetate, equivalent to 3,900–4,900 mg l\(^{-1}\)) and in reactors with hydraulic retention times (HRT) of less than or equal to 10 days, the fast-growing *Methanosarcina* is dominant (Conklin *et al.* 2006) as predicted by the kinetic yields. The greater acetate utilisation rate of *Methanosarcina* suggests that *Methanosarcina*-dominated reactors would be better able to convert acetate to methane, especially when dealing with high loading rates, which could result in a higher volume of produced methane. Whilst reducing the SRT of anaerobic digesters may not be a feasible method of increasing *Methanosarcina* dominance when considered in conjunction with other aims of digestion such as sludge stabilisation, increasing the acetate concentration locally within the digester could potentially be engineered by limitation of the mixing experienced in significant areas of the digester, as demonstrated above. This would prevent the disturbance of pockets of acetate which may form in the digester (Conklin *et al.* 2006).

Whilst it is unlikely that the creation or destruction of localised pockets of high acetate concentrations alone is responsible for the variation in microbiological population structure under changing mixing conditions, it appears that this hypothesis offers some explanation of the results encountered in the experimental work carried out for this research.

**CONCLUSIONS**

In this work, laboratory-scale digesters were modelled using CFD to demonstrate how velocity gradient varies on a local scale. For a range of mixing speeds from 50 to 200 rpm, local velocity gradients of less than 10 s\(^{-1}\) account for 20–85% of the digester volume, with higher volumes of low velocity gradient occurring at lower mixing speeds. Experimental work concluded that within this range of mixing speeds, gas production increased when mixing was reduced from \(G\) of 9.7 to 7.2 s\(^{-1}\). When increased from 9.7 to 14.3 s\(^{-1}\), biogas production fell more than 50%. This suggests that there is an average velocity gradient threshold, above which increased mixing becomes counter-productive and biogas production falls. For these digesters, that threshold lies between 7.2 and 14.3 s\(^{-1}\). Consequently, the effects of minimally mixed zones in anaerobic digesters and the effects of low velocity gradients on digester microbiology should be carefully considered when attempting to maximise biogas production from a digester.

With this in mind, it is suggested that the increased shear stress applied to the sludge at increased levels of turbulence in an anaerobic digester disturbs localised pockets of acetate. This reduces the relative levels of acetoclastic methanogens in comparison to hydrogenotrophic methanogens. In order to fully understand the intermediary links between mixing, micro-organisms and biogas production, it would be beneficial to study more closely micro-organisms in areas of high and low local velocity gradients of a digester, as identified using CFD models. This could lead to greater understanding of a local \(G\) threshold above which micro-organism communities are damaged. Further research is required to assess above what local \(G\) threshold microbiological communities in the digester are damaged.

**ACKNOWLEDGEMENTS**

The authors acknowledge the contributions of an EPSRC CASE award and Severn Trent Water to this project.

**REFERENCES**

ANSYS-Fluent 2010 *Fluent 13.0*. Lebanon, NH.


Griffin, M. E., McMahon, K. D., Mackie, R. I. & Raskin, L. 1998 *Methanogenic population dynamics during start-up of*...


