SUBSTRATE MIXING IN A ROTATING DRUM FERMENTER FOR THE DRY ANAEROBIC DIGESTION OF BIOWASTE

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ABSTRACT

Dry anaerobic digestion (AD) is a proven technology for energy recovery from biowaste. Compared to wet AD, advantages of this technology include: cost effectiveness by high throughputs, lower operation costs, and more compact reactor design for equivalent loading rate, reduced water demand, more simple phase-separation for the digestate, and less pre-treatment requirements. To maximize biogas yields, adequate substrate mixing during AD is of particular importance. In dry AD this may be hampered by high solid matter contents causing a more pronounced wear of mixing tools thereby triggering costly maintenance interruptions. This study aims at the development of a rotating drum fermenter (RDF) to overcome these problems. Rotating drums are known to provide relatively gentle and uniform mixing by the tumbling motion of the solid medium. As a first step towards the development of a full-scale RDF for dry AD of biowaste, particular attention has been given to the mixing performance. Therefore, a lab-scale RDF was designed from acrylic glass to allow visual inspection of the radial mixing process. To reflect the heterogeneous properties of biowaste, several model materials (e.g. grains and seeds as granular matter, straw and wood shavings as bulking material) were selected and characterized. Mixtures of these materials were soaked in water and a polymeric suspension was added to achieve desired viscosity. The slump test was used to estimate the yield stress of the mixtures. To quantify the state of mixing via image analysis, a dye tracer technique was applied. For the viscous substrates tested a continuous flow pattern was observed similar to the rolling regime of granular material with the difference that thickness of the active layer was markedly enlarged. The mixing performance of the RDF found in our experiments could be improved by a single baffle mounted on the inner wall of the RDF. Using a baffle length of 0.16 m at an RDF filling degree of 0.80 and a rotation frequency of 1 min^{-1} the mixing performance could be significantly increased compared to a set-up without baffle. The number of rotations required to reach a well-mixed state also depends on the rheologic characteristics of the substrate accessible from the results of the slump test.

Keywords: Anaerobic digestion, biowaste, rotating drum fermenter, mixing, slump test

1. Introduction

Biowaste is a highly degradable substrate (Mata-Alvarez *et al.,* 2014) and is a complex and heterogeneous mixture in terms of structure, composition and size. Thus, one major challenge during dry anaerobic digestion (AD) is related to the physical characteristics of the feed: on account of low water content, its “apparent viscosity’’ is high and technical equipment is required for transporting the fresh feed and mixing it with the partially digested waste in the reactor (Garcia-Bernet *et al.,* 2011). In most cases, sufficient fluidity of the raw feed (biowaste) is attained by recirculating the liquid phase of the digested output. To maximize biogas yields, adequate substrate mixing during AD is of particular importance. In dry AD mixing may be hampered by high total solid matter (TS) contents causing a pronounced wear of mixing tools thereby triggering costly maintenance interruptions. Indeed, paddle mixers are the most critical component of plug-flow fermenters for dry AD of biowaste (Görisch and Helm, 2007).

The above-named problems may be circumvented by digestion in a rotating drum. Rotating drums are known to provide relatively gentle and uniform mixing by the tumbling motion of the solid medium and have been used as bioreactors for solid-state fermentation since the 1930s (Mitchell *et al*., 2006). Current industrial-scale applications include the continuous aerobic composting of municipal biowaste. However, until now only little attention has been paid to the performance of dry AD in rotary drum fermenters (RDF). A series of lab-scale (volume = 3.7 L) RDF studies were performed by Jiang *et al.* (2002). There, the main focus was given to the description and management of the microbiological processes (e.g. the effect of hydraulic retention time and stirring media on acidogenesis). Less attention was paid to the mixing efficiency of the RDF.

The primary concern in designing a rotating drum reactor is the internal solid motion because it plays an important role in heat and mass transfer phenomena (Grajales *et al.,* 2012). In the rotating drum literature, the most commonly used material for mixing experiments are dry granular particles (Nase *et al.*, 2001). More recent studies have been dealing with wet granular materials and the effect of interstitial fluid viscosity on the segregation and flow-patterns in rotating drums (Chou *et al.*, 2011). However, those materials are still far from representing typical substrates for dry AD regarding heterogeneity in particle size and moisture content. Knowledge concerning the flow and mixing behaviour of such materials in rotating drum reactors is sparse.

This study aims at the development of a rotating drum fermenter to overcome suboptimal gas yields due to insufficient homogenization of typical substrates of AD. As a first step towards the development of a full-scale RDF for dry AD of biowaste, particular attention was given to the mixing performance. As a prerequisite to this reproducible model materials needed to be provided and identified.

2. Materials and methods

2.1. Model substrate pre-treatment

To reflect the heterogeneous properties of biowaste, several model materials differing in granulometric properties were selected and characterized as single substrates as well as viscous mixtures thereof. Granular materials (GM, wheat grains, mustard seeds and maize kernels) were selected to reflect particular biowaste components like vegetables, fruits and food waste. Straw, wood shavings, hemp bedding and cotton litter was selected as bulking material (BM). The selection criteria were colourability and water uptake behaviour.

The viscous model substrate consisted of equal shares of dyed and native (non-dyed) mixtures of GM and BM. A concrete mixer was used both for pre-soaking the materials and the production of the dyed aliquots using methylene blue (Merck, Germany) as a colorant. To trace the mixing process the native and dyed model substrates were filled into the reactor as two distinct horizontal layers of uniform volume. Pre-soaking for 16 h served to provide a moisture content typical for biowaste (20% < TS < 50%) and to avoid changes of the material properties during the mixing experiments. After pre-soaking/dyeing excess the water was removed by sieving. A polymeric suspension (PS) was then added to achieve desired viscosity based on the yield stress of a real anaerobic digestate (KOMPOGAS dry AD, Fulda), which was found to range between 150 Pa and 300 Pa. This is within the lower range of reported literature values between (150 and 900 Pa; Garcia-Bernet *et al.*, 2011). The suspension contained semolina and wheat bran as fines and 0.1% xanthan and had a total dry matter content of 13% wt.

The slump of the model substrate was used as a measure of the yield stress (τ) which dominates the rheological behaviour of biomass slurries such as pre-treated corn stover (Stickel *et al*., 2009). The slump was previously employed by other researchers to characterize anaerobic digestates (Baudez *et al*., 2004; Garcia-Bernet *et al*., 2011). The experimental set-up for yield stress measurements was adopted from Baudez *et al*. (2004).

2.2. Experimental

To study the radial (two dimensional) mixing process, a lab-scale RDF (diameter 0.5 m, length 0.3 m, volume 50 L) made of PMMA (acrylic glass) was used. This allowed for the visual inspection of the substrate. The turning motion was achieved by an electric motor attached to a transmission chain mounted on a quill shaft. The latter may also serve as the feed inlet during transient mixing experiments, if required.

To study the effect of baffles on the dynamics of the mixing process one evenly spaced straight baffle with a length of 0.16 m (64% of the RDF radius) was fixed normal to the drum wall. The mixing experiments were conducted at a rotation frequency of 1 min^{-1}.

3. Results and discussion

3.1. Mixing behaviour of viscous substrates and the effect of a baffle

The composition and characteristics of the tested substrates are as follows: Substrate 1 (GM: 47%, BM: 9.5%, PS: 43%, TS: 35%, τ: 166 Pa) and Substrate 2 (GM: 33%, BM: 28%, PS: 39%, TS: 29%, τ: 500 Pa). Obviously, TS and yield stress are not clearly correlated. This indicates that TS does not adequately predict the rheological properties. A stronger influence on the yield stress was found for the fraction of BM due their interlocking properties. However, the general hydrodynamic behaviour for both substrates found in a RDF without baffle was very similar (not shown).

Figure 1 depicts the radial mixing progress for substrate 1 and 2 with and without baffle respectively. Note that the initial position of dyed and non-dyed substrates for both runs is inverted. Substrate 1 showed a better degree of mixing after 15 revolutions (rev.). For substrate 2, mixing as judged by the distribution of blue and native layers was unsatisfactory even after 25 rev. (Figure 1 H), indicating that in the absence of baffles mixing time increased substantially. The latter could be detrimental to mass and heat transfer between the substrate bed and the gas-phase. It is also noteworthy that mixing performance could be improved with only a single baffle. The most commonly reported design for rotating drum fermenters is to mount four baffles opposite to each other. However, a smaller number may be economically more favourable by reducing the specific power consumption (Wang *et al*., 2013).

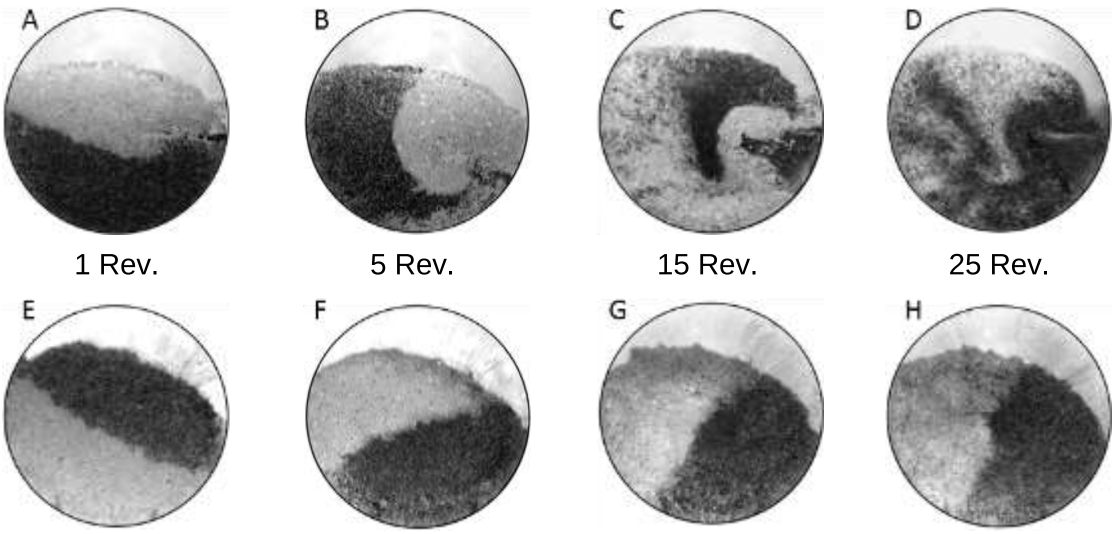

Figure 1: Comparison of the radial mixing progress for substrate 1 (A-D, with baffle) and substrate 2 (E-H, without baffle) at 1, 5, 15 and 25 rev. of the RDF (fill level: 0.80).

3.2. Hydrodynamic behaviour

At the given slow rotation frequency of the RDF ($\approx$1 rpm) a discontinuous slumping motion (avalanching) can be expected for GM where each avalanche ceases completely before the next begins (Metcalfe and Shattuck, 1996). However, for the viscous substrates tested a rather continuous flow pattern was observed, i.e. no intermittent avalanching took place. The observed flow pattern was more similar to the rolling regime of GM with the difference that the thickness of the active layer was markedly enlarged ($\approx$ 28% of the material height at the midpoint of the slope). This flow pattern is represented in Figure 2A. It is important to note, that the baffle while crossing through the lower position had no effect on the flow pattern of the active layer and is therefore comparable to a RDF without any baffle.

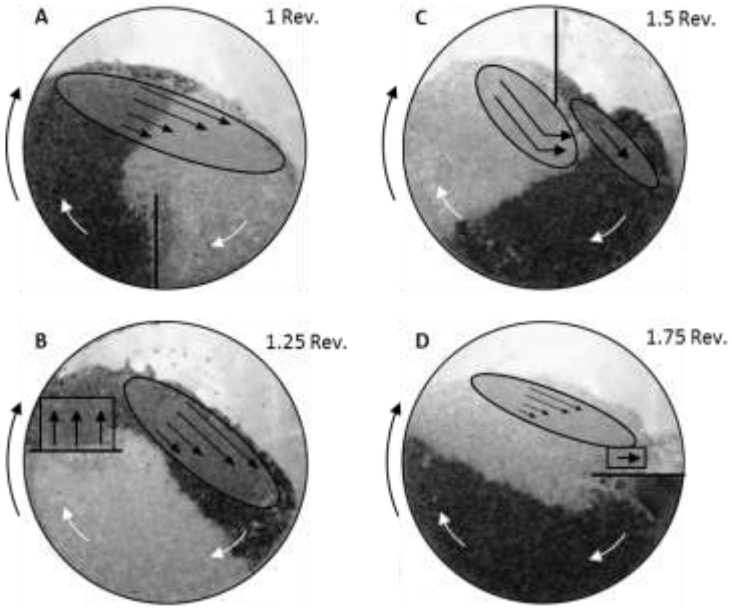

Figure 2: Flow patterns for substrate 1 inside the RDF (fill level: 0.80) influenced by a baffle (L = 0.16 m).

The effect that the baffle mounted inside the RDF had on the particle flow pattern is shown in Figure 2 B-D. In contrast to the experiments without baffles, which showed only two zones (an active layer and a solid body), the experiments with a baffle in the RDF exhibited several zones with distinct flow patterns: After reaching the left centre position the baffle has a lifting effect on the material, whereby the slope of the active layer is increased (see Figure 2 B). During passage of the “12 o’clock”-position the baffle caused a material flow through the centre region (see Figure 2 C) increasing the mixing performance. Re-immersion of the baffle into material leads to a temporary entrapment of air in front of and behind the baffle (Figure 2 D).

4. Conclusions

The radial mixing performance of the RDF for viscous substrates in absence of a baffle was unsatisfactory. The number of rotations necessary to reach a well-mixed state was substantially decreased in the presence of a single baffle mounted on the inner wall of the RDF.

To more realistically mimic the rheology of real biowaste substrates during AD, various granular and bulking materials were mixed and blended with a polymeric suspension. The slump test was successfully applied to estimate the yield stress for those heterogeneous substrates. Ongoing research is devoted to the relationship between the rheological characteristics and the resulting radial and axial mixing behaviour of viscous and heterogeneous substrates. Future work will also focus on the entropy of mixing as a quantitative approach in the image analysis of the mixing process as well as axial transport and three-dimensional mixing of such substrates.

REFERENCES

1. Baudez, J.-C., Ayol, A. and Coussot, P. (2004), Practical determination of the rheological behavior of pasty biosolids. J. Environ. Man., **72** (3), 181-188.
2. Chou, S. H.; Liao, C. C. and Hsiau, S. S. (2011), The effect of interstitial fluid viscosity on particle segregation in a slurry rotating drum, Phys. Fluids **23** (8), 83301
3. Garcia-Bernet, D., Loisel, D., Guizard, G., Buffière, P., Steyer, J. P. and Escudié, R (2011), Rapid measurement of the yield stress of anaerobically-digested solid waste using slump tests. Waste Management, **31** (4), 631-635.
4. Grajales, L. M., Xavier, N. M., Henrique, J. P. and Thoméo, J. C. (2012), Mixing and motion of rice particles in a rotating drum, Powder Tech., **222**, 167-175.
5. Görisch, U., and Helm, M. (Ed.) (2007), Biogasanlagen: Planung, Errichtung und Betrieb von landwirtschaftlichen und industriellen Biogasanlagen, 2nd edn. Ulmer, Stuttgart (Hohenheim).

6. Jiang, W. Z., Kitamura, Y., Ishizuka, N. and Liang, T. (2002), A Rotational Drum Fermentation System (RDFS) for Dry Methane Fermentation (1), J. Soc. Agricult. J., **33** (3), 85-92.
7. Mata-Alvarez, J., Dosta, J. Romero-Güiza, M. S., Fonoll, X., *et al*. (2014), A critical review on anaerobic co-digestion achievements between 2010 and 2013, Renew. Sust. Energ. Rev., **36**, 412-427.
8. Metcalfe, G., & Shattuck, M. (1996), Pattern formation during mixing and segregation of flowing granular materials, Fractals and Statistical Mech., **233** (3-4), 709-717.
9. Mitchell, D. A., Berovic, M. and Krieger, N. (Ed.); (2006), Solid-State Fermentation Bioreactors: Fundamentals of Design and Operation. Springer Berlin Heidelberg.
10. Nase, S. T.; Vargas, W. L.; Abatan, A. A. and McCarthy, J. J (2001), Discrete characterization tools for cohesive granular material, Powder Tech. **116** (2-3), 214-223.
11. Stickel, J. J., Knutsen, J. S., Liberatore, M. W., Luu, W., Bousfield, D. W., Klingen-berg, D. J. *et al.* (2009), Rheology measurements of a biomass slurry: an inter-laboratory study, Rheol. Acta, **48** (9), 1005-1015.
12. Wang, Z.; Wen, S.; Zhang, Q.; Liu, G.; Wu, X. and Cong, W. (2013), Power Consumption of Liquid and Liquid/Solid Systems in a Rotating-Drum Bioreactor. Chem. Eng. Technol., **36** (8), 1395-1401.