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Rheological Characterization

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1. Introduction

The biogas process has long been a part of our biotechnical solutions for the handling of sewage sludge and waste. However, in many cases the existing process applications need to be optimized to improve the extent of biogas production as a part of the energy supply in a sustainable and viable society. Although the principles are well known, process disturbances and poor substrate utilization in existing biogas plants are common and are in many cases likely linked to changes in the substrate composition.

Changes in substrate composition can be done as a means to obtain a more efficient utilization of existing biogas facilities, which today treating mainly manure or sewage sludge. By bring in more energy rich residues and wastes a co-digestion process with higher biogas potential per m³ volatile solids (VS) can often be obtained. However, new and changing feedstocks may result in shift in viscosity of the process liquid and, hence, problems with inadequate mixing, break down of stirrers and foaming. These disturbances may seriously affect the degradation efficiency and, hence, also the gas-production per unit organic material digested. In turn, operational malfunctions will cause significant logistic problems and increased operational costs. Changes of the substrate profile for a biogas plant may also infer modifications of the downstream treatment of the digestate.

Together with high digestion efficiency, i.e. maximum methane formation per reactor volume and time, the economy of a biogas plant operation depends on the energy invested to run the process. A main part of the energy consumed during operation of continuous stirred tank reactors (CSTRs) is due to the mixing of the reactor material (Nordberg and Edström, 2005). The shear force needed is dependent on the viscosity of the reactor liquid, where increasing viscosity demands a higher energy input. Active stirring must be implemented in order to bring the microorganisms in contact with the new feedstock, to facilitate the upflow of gas bubbles and to maintain an even temperature distribution in the digester. Up to 90% of biogas CSTR plants use mechanical stirring equipment (Weiland *et al.*, 2010).

In this context the rheological status of the reactor liquid as well as of the residual digestate are important for process mixing design and dimensioning. In addition experiences on rheological characterisation of sewage sludge revealing their dependence on the suspended

solid concentration and on the characteristics of the organic material as well as on the interactions between particles and molecules in the solution (Foster, 2002). Therefore, this type of characterisation can be important in process monitoring and control.

The aim of this chapter is to briefly introduce the area of rheology and to present important parameters for rheological characterization of biogas reactor fluids. Examples are given from investigations on such parameters for lab-scale reactors digesting different substrates.

2. Rheology

Rheology describes the deformation of a body under the influence of stress. The nature of the deformation depends on the body's material conditions (Goodwin & Hughes, 2000). Ideal solids deform elastically, which means that the solid will deform and then return to its previous state once the force ceases. In this case, the energy needed for deformation will mainly be recovered after the stress terminates. If the same force is applied to ideal fluids, it will make them flow and the energy utilized will disperse within the fluid as heat. Thus, the energy will not be recovered once the forcing stress is terminated (Goodwin & Hughes, 2000).

For fluids a flow curve or rheogram is used to describe rheological properties. These properties may be of importance in anaerobic digestion for the dimensioning of e.g. feeding, pumping and stirring. Rheograms are constructed by plotting shear stress (τ) as a function of the shear rate (γ) (Tixier *et al.*, 2003; Guibad *et al.*, 2005).

The stress applied to a body is defined as the force (F) divided by the area (A) over which this force is acting (Eq. 1). When forces are applied in opposite directions and parallel to the side of the body it is called shear stress (Goodwin & Hughes, 2000). Shear stress (τ ; Pa) is one of the main parameters studied in rheology, since it is the force per unit area that a fluid requires to start flowing (Schramm, 2000). The shear rate (γ ; s⁻¹) describes the velocity gradient (Eq. 2). Hence, shear rate is the speed of a fluid inside the parallel plates generated when shear stress is applied (Pevero & Guibad, 2005).

$$\tau = F/A = \text{N/m}^2 = \text{Pa} \quad (1)$$

$$\gamma = dv_x/dy = (\text{m/s})/\text{m} \quad (2)$$

2.1 Newtonian fluids

Ideal fluids (e.g. water, methanol, olive oil and glycerol) perform linearly in rheograms, as illustrated for glycerol in figure 1, and are identified as Newtonian fluids. The Newtonian equation (Eq. 3) illustrates the flow behaviour of an ideal liquid (Schramm, 2000), where η is the viscosity (Pa*s). Dynamic viscosity, also called apparent viscosity, describes a fluid's resistance of deformation (Pevero & Guibad, 2005). In terms of rheology it is the relation of shear stress over the shear rate (Eq. 4). For Newtonian fluids the dynamic viscosity maintains a constant value meaning a linear relationship between τ and γ .

$$\tau = \eta * \gamma \quad (3)$$

$$\eta = \tau / \gamma \quad (4)$$

When measuring the dynamic viscosity, the fluid is subjected to a force impact caused by moving a body in the fluid. Resistance to this movement provides a measure of fluid viscosity. The dynamic viscosity can be measured using a rotation rheometer. The device consists of an external fixed cylinder with known radius and an internal cylinder or spindle with known radius and height. The space between the two cylinders is filled with the fluid subjected to dynamic viscosity analysis.

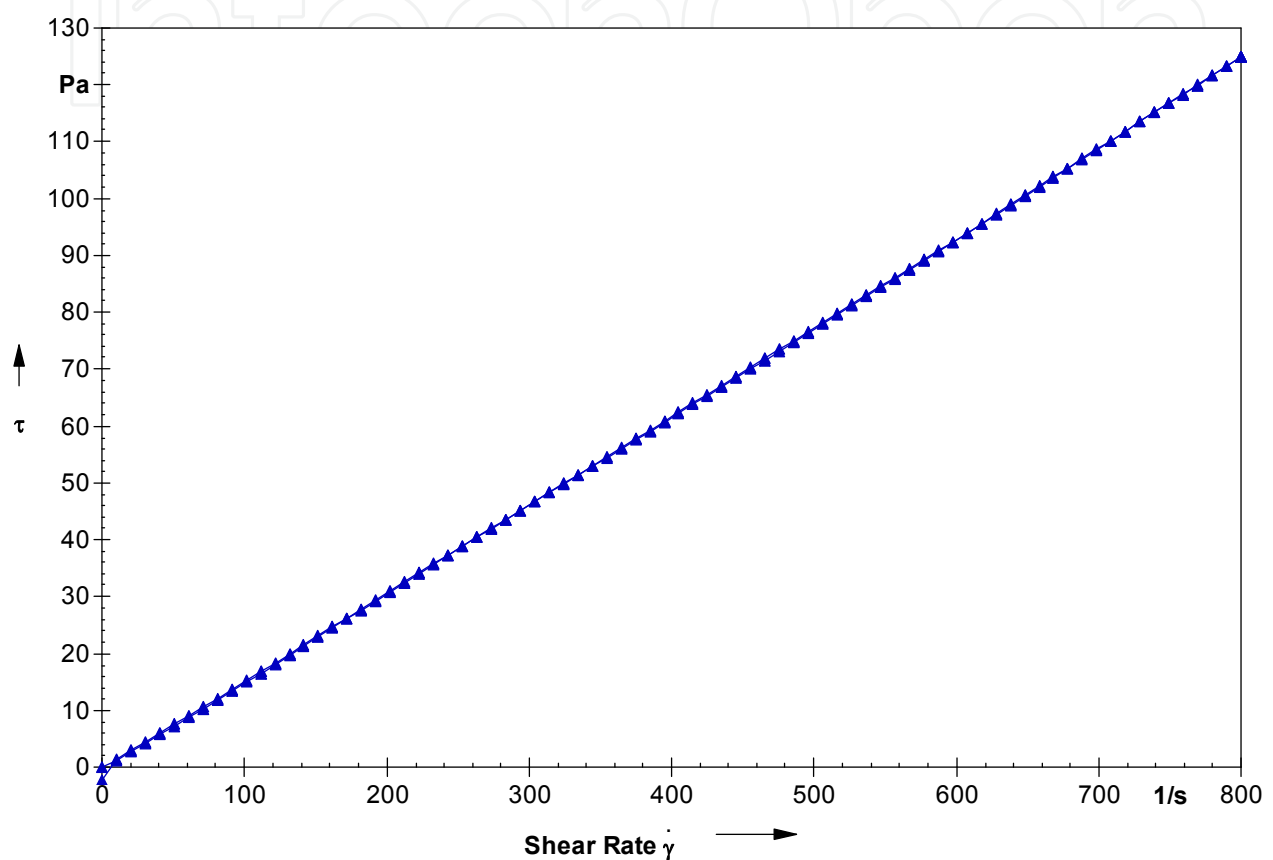


Fig. 1. Rheogram – flow curve of glycerol (\blacktriangle) at 20 °C with a linear relationship between shear stress (τ ; Pa) and shear rate ($\dot{\gamma}$; s⁻¹), representing a Newtonian liquid.

2.2 Limit viscosity

Limit viscosity (η_{lim}) corresponds to the viscosity of a fluid at the maximum dispersion of the aggregates under the effect of the shear rate (Tixier & Guibad, 2003). The limit viscosity is estimated through the rheogram, when the dynamic viscosity becomes linear and constant. This parameter has been shown to be of great value when studying the rheological characteristics of sludge, since it determines the level of influence of important factors such as the total solids fraction (TS; Lotito *et al.*, 1997). TS (%) and volatile solids (VS, % of TS) are parameters measured in the biogas process in order to control the amount of solids that may be transformed to methane. Also, Pevere and Guibad (2005) reported that the limit viscosity was sensitive to the physicochemical characteristics of granular sludge, i.e. it was influenced by changes in the particle size or the zeta potential.

2.3 Dynamic yield stress

Yield stress (τ_0) is defined as the force a fluid must be exposed to in order to start flowing. It reflects the resistance of the fluid structure to deformation or breakdown. Rheograms from rotational viscometer measurements are used as a means to calculate yield stress. It can also be obtained by applying rheological mathematical models (section 2.6; Spinoso & Loito 2003). Yield stress is important to consider when mixing reactor materials, since the yield stress is affecting the physico-chemical characteristics of the fluid and impede flow even at relative low stresses. This might lead to problems like bulking or uneven distribution of material in a reactor (Foster, 2002).

2.4 Static yield stress

The static yield stress (τ_s) is the yield stress measured in an undisturbed fluid while dynamic yield stress is the shear stress a fluid must be exposed to in order to become liquid and start flowing. The fact that both dynamic yield stress and static yield stress sometimes may appear is explained by the existence of two different structures of a fluid. One structure is not receptive to the shear stress and tolerates the dynamic yield stress, while a second structure (a weak gel structure) is built up after the fluid has been resting a certain period of time (Yang *et al.*, 2009). When these two structures merge, a greater resistance to flow is generated translated to the static yield stress.

The formation of the weak gel structure may be a result from chemical interactions among polysaccharides or between proteins and polysaccharides (Yang *et al.*, 2009). The weak gel structure is quite vulnerable and, thus easily interrupted by increasing shear rates.

2.5 Non-Newtonian fluids

Non-Newtonian fluids do not show a linear relationship between shear stress and shear rate. This is due to the complex structure and deformation effects exhibited by the materials involved in such fluids. The non-Newtonian fluids are however diverse and can be characterised as e.g. pseudoplastic, viscoplastic, dilatant and thixotropic fluids (Schramm, 2000).

2.5.1 Pseudoplastic fluids

Pseudoplastic fluids become thinner when the shear rate increases, until the viscosity reaches a plateau of limit viscosity. This behaviour is caused by increasing the shear rate and the elements suspended in the fluid will follow the direction of the current. There will be a deformation of fluid structures involving a breaking of aggregates at a certain shear rate and this will cause a limit in viscosity. For pseudoplastic fluids the viscosity is not affected by the amount of time the shear stress is applied as these fluids are non-memory materials i.e. once the force is applied and the structure is affected, the material will not recover its previous structure (Schramm, 2000). Some examples are corn syrup and ketchup.

2.5.2 Viscoplastic fluids

Viscoplastic fluids, such as e.g. hydrocarbon greases, several asphalts and bitumen, behave as pseudoplastic fluids upon yield stress. They need a predetermined shear stress in order to

start flowing. One type of these, the Bingham plastic, requires the shear stress to exceed a minimum yield stress value in order to go from high viscosity to low viscosity. After this change a linear relationship between the shear stress and the shear rate will prevail (Ryan, 2003). Examples of Bingham plastic liquids are blood and some sewage sludge's.

2.5.3 Dilatant fluids

Dilatant fluids become thicker when agitated, i.e. the viscosity increases proportionally with the increase of the shear rate. Like for the pseudoplastic fluids the stress duration has no influence, i.e. when the material is disturbed or the structure destroyed it will not go back to its previous state. Some examples of shear thickening behaviour are honey, cement and ceramic suspensions.

2.5.4 Thixotropic fluids

Thixotropic fluids are generally dispersions, which when they are at rest construct an intermolecular system of forces and turn the fluid into a solid, thus, increasing the viscosity. In order to overcome these forces and make the fluid turn into a liquid and which may flow, an external energy strong enough to break the binding forces is needed. Thus, as above a yield stress is needed. Once the structures are broken, the viscosity is reduced when stirred until it receives its lowest possible value for a constant shear rate (Schramm, 2000). In opposite to pseudoplastic and dilatant fluids, the viscosity of thixotropic fluids is time dependent: once the stirring has ended and the fluid is at rest, the structure will be rebuilt. This will inform about the fluid possibilities of being reconstructed. Wastewater and sewage sludge can be examples of fluids with thixotropic behaviour (Seysiecq & Ferasse, 2003) as well as paints and soap.

2.6 Rheological mathematical models

There are several rheological mathematical models applied on rheograms in order to transform them to information on fluid rheological behaviour. For non-Newtonian fluids the three models presented below are mostly applied (Seysiecq & Ferasse, 2003).

2.6.1 Herschel Bulkley model

The Herschel Bulkley model is applied on fluids with a non linear behaviour and yield stress. It is considered as a precise model since its equation has three adjustable parameters, providing data (Pevero & Guibaud, 2006). The Herschel Bulkley model is expressed in equation 5, where τ_0 represents the yield stress.

$$\tau = \tau_0 + K * \dot{\gamma}^n \quad (5)$$

The consistency index parameter (K) gives an idea of the viscosity of the fluid. However, to be able to compare K-values for different fluids they should have similar flow behaviour index (n). When the flow behaviour index is close to 1 the fluid's behaviour tends to pass from a shear thinning to a shear thickening fluid. When n is above 1, the fluid acts as a shear thickening fluid. According to Seysiecq and Ferasse (2003) equation 5 gives fluid behaviour information as follows:

- $\tau_0 = 0$ & $n = 1 \Rightarrow$ Newtonian behaviour
 $\tau_0 > 0$ & $n = 1 \Rightarrow$ Bingham plastic behaviour
 $\tau_0 = 0$ & $n < 1 \Rightarrow$ Pseudoplastic behaviour
 $\tau_0 = 0$ & $n > 1 \Rightarrow$ Dilatant behaviour

2.6.2 Ostwald model

The Ostwald model (Eq. 6), also known as the Power Law model, is applied to shear thinning fluids which do not present a yield stress (Pevere *et al.*, 2006). The n-value in equation 6 gives fluid behaviour information according to:

$$\tau = K * \gamma^{(n-1)} \quad (6)$$

- $n < 1 \Rightarrow$ Pseudoplastic behaviour
 $n = 1 \Rightarrow$ Newtonian behaviour
 $n > 1 \Rightarrow$ Dilatant behaviour

2.6.3 Bingham model

The Bingham model (Eq. 7) describes the flow curve of a material with a yield stress and a constant viscosity at stresses above the yield stress (i.e. a pseudo-Newtonian fluid behaviour; Seyssiecq & Ferasse, 2003). The yield stress (τ_0) is the shear stress (τ) at shear rate (γ) zero and the viscosity (η) is the slope of the curve at stresses above the yield stress.

$$\tau = \tau_0 + \eta * \gamma \quad (7)$$

- $\tau_0 = 0 \Rightarrow$ Newtonian behaviour
 $\tau_0 > 0 \Rightarrow$ Bingham plastic behaviour

3. Rheological characterization of biogas reactor fluids

When considering the rheology for biogas reactors their viscosity is estimated to correspond to a given TS of the reactor fluid. This is mainly based on historically rheological data from sewage sludge with known TS values. However, problems may arise when using these TS relationships for other types of substrates which may impose other rheological characteristics of the reactor fluids. Furthermore, often low consideration is given to possible viscosity changes due to variation in feedstock composition etc.

Shift in the viscosity and elasticity properties of the reactor material related to substrate composition changes can alter the prerequisites for the process regarding mixing (dimension of stirrers, pumps etc. or reactor liquid circulation) and likely also foaming problems (Nordberg & Edström, 2005; Menéndez *et al.*, 2006). It may also call for changes in the post treatment requirements and end use quality of the organic residue e.g. dewatering ability, pumping and spreading on arable land (Baudez & Coussot, 2001). The additions of enzymes can be used to reduce the viscosity of the substrate mixture in the digester significantly and avoid the formation of floating layers (Weiland, 2010; Morgavi *et al.*, 2001). All these factors affect the total economy for a biogas plant.

In this context differences in the rheological characteristics of biogas reactor fluids as depending on substrate composition were analyzed and used as examples in this presentation.

3.1 Rheological measurements

A rotational rheometer RheolabQC coupled with Rheoplus software (Anton Paar) was used for different reactor fluids, which recorded the rheograms and allowed subsequent data analysis. The temperature was maintained constant at 37 ± 0.2 °C. The reactor fluid volume used for each measurement was 17 ml. Reactor fluids from mesophilic (37°C) lab-scale reactors (4 L running volume), with a hydraulic retention time (HRT) of 20 days, were sampled.

Five lab-scale reactors (A-E) were sampled before the daily feeding of substrates. All reactors had been running for at least three HRTs prior to sampling. The different substrates treated were slaughter household waste, biosludge from pulp- and paper mill industries, wheat stillage and cereal residues. The TS values ranged between 3.1–3.9 % for four of the reactors while one was at 7.7 % (Table 1).

Reactor	Digested substrate	TS (%)
A	Slaughter house waste	3.9
B	Biosludge from pulp- and paper mill industry 1	3.8
C	Biosludge from pulp- and paper mill industry 2	3.7
D	Wheat stillage	3.0
E	Cereal residues	7.7

Table 1. Fluids from five lab-scale reactors were chosen for rheological measurements. A short description of their TS values and substrates are presented.

Rheological measurements were carried out with a three-step protocol where (1) the shear rate increased linearly from 0 to 800 s^{-1} in 800 sec., (2) maintaining constant shear rate at 800 s^{-1} in 30 sec, (3) decreasing linearly the shear rate from 800 to 0 s^{-1} in 800 sec., according to Björn *et al.* (2010). For each sample three measurements were carried out and performed immediately after sampling or stored at +4 °C pending analysis.

The fluid behaviour was interpreted by the flow- and viscosity curves according to Schramm (2000), and the dynamic viscosity, limit viscosity and yield stress were noticed. The three most common mathematical models for non-Newtonian fluids; Herschel Bulkley model; Ostwald model (Power Law) and Bingham model, were applied in order to transform rheogram data values to the rheological behaviour of the fluids. Flow behaviour index (n) and consistency index (K) were studied.

3.2 Flow and viscosity behaviour characteristics

The flow curves for reactor fluids A-E (Figures 2–3) indicated different flow behaviour according to the definitions by Schramm (2000). A Newtonian behaviour of reactors A and D, fed with slaughter house waste and wheat stillage, respectively, was illustrated where the exerted shear stress was almost proportional to the induced shear rate. However, a small yield stress of 0.2 Pa and 0.3 Pa were detected, indicating a pseudo-Newtonian behaviour.

Fluids from reactor B, receiving biosludge from paper mill industry 1 as substrate, indicated an unusual performance at the beginning of the rheogram with decreasing shear stress, thereafter a linear increase in shear stress. A yield stress of 14 Pa was detected. A space

between the curves was noticeable when the shear rate increased and afterwards decreased for reactor B (Fig. 2). This area describes the degree of thixotropy of this fluid, which means that the increase of this area is related to the amount of energy required to breaking down the thixotropic structure. Thus, the flow curves obtained with the three-step protocol indicated a thixotropic behaviour of reactor fluid B.

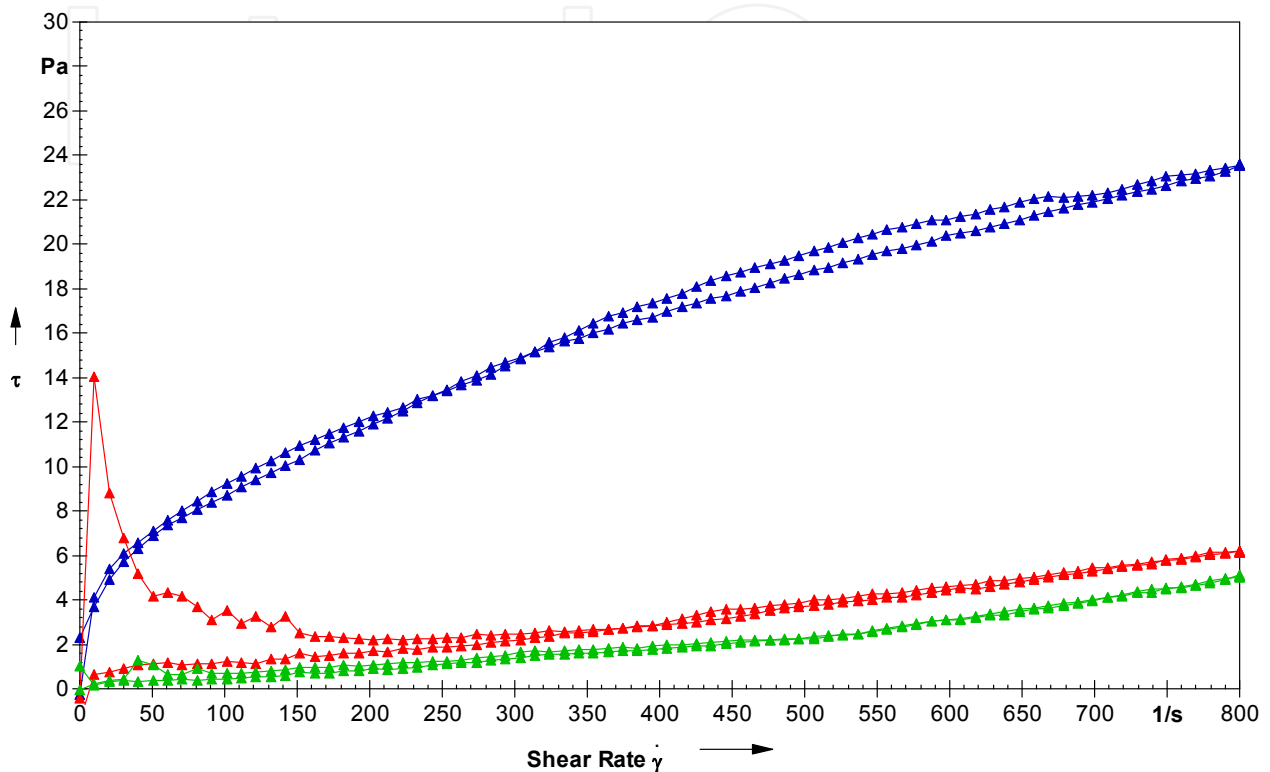


Fig. 2. Rheogram - flow curves illustrating shear stress (τ ; Pa) vs shear rate (γ ; s^{-1}) for fluids from reactor A (\blacktriangle), B (\blacktriangle) and C (\blacktriangle) with a three-step protocol.

Reactors C and E revealed viscoplastic behaviours, i.e. a pseudoplastic behaviour with yield stress. Reactor C, fed with biosludge from paper mill industry 2, showed a yield stress of 4 Pa (Fig. 2), and reactor E, receiving cereal residues, a yield point of 4.5 Pa (Fig. 3). The yield stress is defined as the force that a fluid must overcome in order to start flowing (Spinosa & Lotito, 2003). Also for reactor E, a small space between the curves was noticeable when the shear rate increased and afterwards decreased (Fig. 3). This area difference might indicate some degree of thixotropy.

Reactor	Flow curve behaviour	Viscosity curve behaviour
A	Newtonian; pseudo-Newtonian	Viscoplastic (pseudo-Newtonian)
B	Thixotropic	Thixotropic
C	Viscoplastic	Viscoplastic
D	Newtonian; pseudo-Newtonian	Pseudoplastic or viscoplastic
E	Viscoplastic	Viscoplastic

Table 2. The flow and viscosity curves for reactor fluids A-E indicated different fluid behaviour according to Schramm (2000).

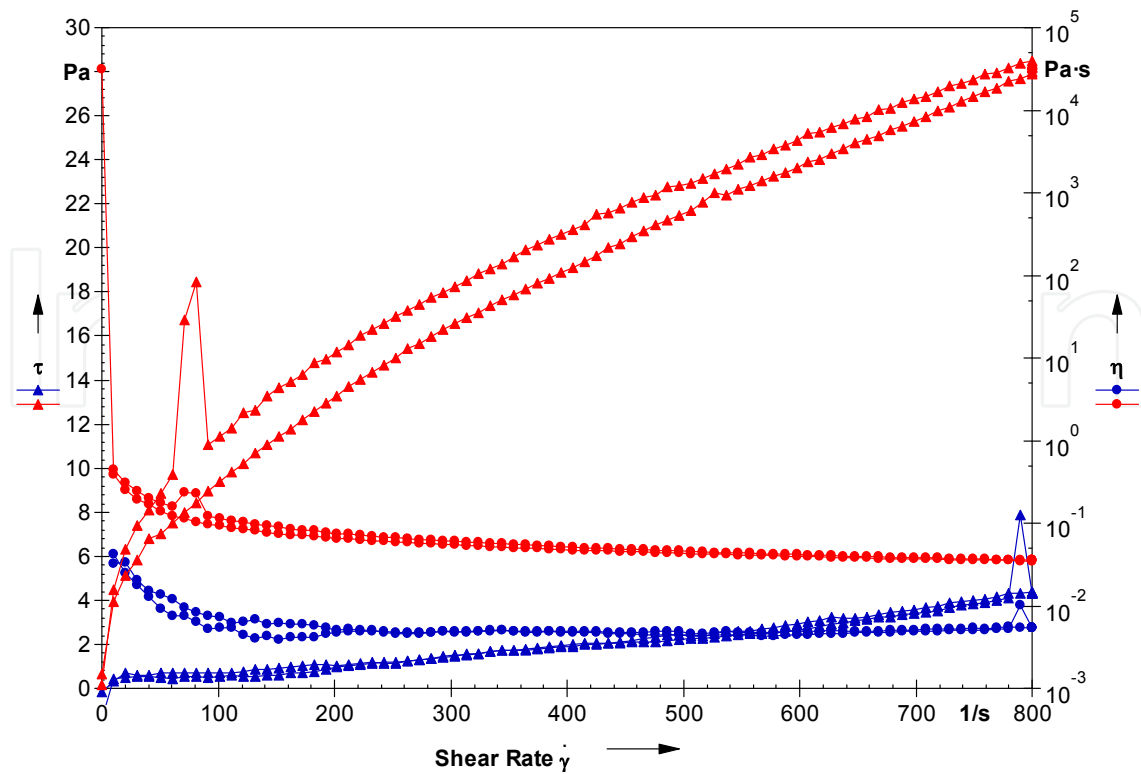


Fig. 3. Rheogram - flow and viscosity curves for reactors D (▲; ●) and E (▲; ●) with a three-step protocol. Flow curves illustrating shear stress (τ ; Pa) vs shear rate ($\dot{\gamma}$; s^{-1}) and viscosity curves illustrating dynamic viscosity (η ; Pa*s) vs shear stress ($\dot{\gamma}$; s^{-1}).

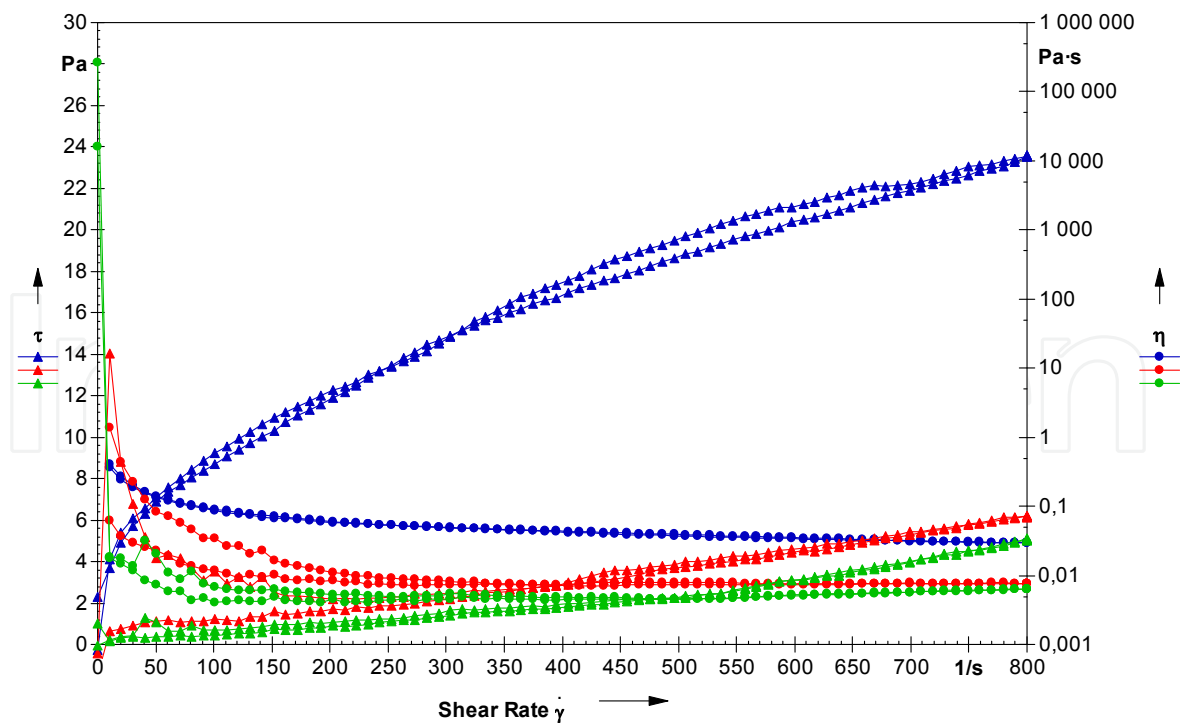


Fig. 4. Rheogram - flow and viscosity curves for reactors A (▲; ●), B (▲; ●) and C (▲; ●) with a three-step protocol. Flow curves illustrating shear stress (τ ; Pa) vs shear rate ($\dot{\gamma}$; s^{-1}) and viscosity curves illustrating dynamic viscosity (η ; Pa*s) vs shear stress ($\dot{\gamma}$; s^{-1}).

The viscosity curves (Figures 3–4) did almost correspond to the flow curve behaviour for the investigated biogas reactor fluids (Table 2). Using the scheme by Schramm (2000) the viscosity curves for reactor A indicated a viscoplastic liquid and for reactor D a viscoplastic or pseudoplastic liquid. The viscosity initially dropped very quickly for reactor A, specifically indicating Bingham viscoplastic fluids with pseudo-Newtonian behaviour. Generally for reactors A–E, the viscosity decreased with increasing shear rate, until it reached its limit viscosities (Table 3).

Reactor	Treated substrate	TS (%)	Dynamic viscosity (mPa*s)	Limit viscosity (mPa*s)
A	Slaughter house waste	3.9	18	6
B	Biosludge paper mill industry 1	3.8	436	8
C	Biosludge paper mill industry 2	3.7	267	29
D	Wheat stillage	3.0	33	6
E	Cereal residues	7.7	443	36

Table 3. The initial dynamic viscosity and the limit viscosity obtained during interval 1 in the 3-step protocol analysis for each reactor fluid.

The limit viscosities ranged 6–36 mPa*s with the highest value for reactor E (Table 3). However, the limit viscosity was similar for reactor C and E despite a difference in TS (%). The dynamic viscosity ranged 18–443 mPa*s for the reactor fluids (Table 3). The reactors A and D showed lower dynamic viscosity values compared to reactor B, C and E, possibly due to their pseudo-Newtonian behaviour. Also, there was a difference in dynamic viscosity between reactor fluids B and C both receiving biosludge with similar TS (%) but coming from two different paper mill industries in Sweden. Thus, the results demonstrated that similar TS values do not necessarily correspond to similar dynamic or limit viscosity values. This contradicts the results presented by Tixier and Guibad (2003), who reported that an increase in TS for activated sludge corresponded to a higher limit viscosity and higher yield stress. Nor, did biosludge from two different Swedish pulp- and paper mill industries with similar TS give similar viscosity values.

Samples from reactor B showed different rheological behaviour depending on when they were measured. The yield stress and viscosity increased when the reactor fluids had been stored and resting compared to when analyzed immediately after sampling, indicating thixotropic behaviour. Figure 5 illustrates how the B reactor fluid after been resting for 48 hours showed a resistance to flow, known as static yield stress. This value (24 Pa) decreased until it reached the dynamic yield stress (7 Pa), which was the value needed in order to become liquid and start flowing. When the analysis was done right after the first measurement (Second measurement), the fluid had already been stirred, so the two different structures that form the resistance to flow were now mixed and no static yield stress was detected. The static yield stress might be initiated by several factors, e.g. weakness of the fluid structure, low mixed liquid solid suspension (MLSS) concentration, small size of particles and poor dewater ability (Pevere *et al.* 2006).

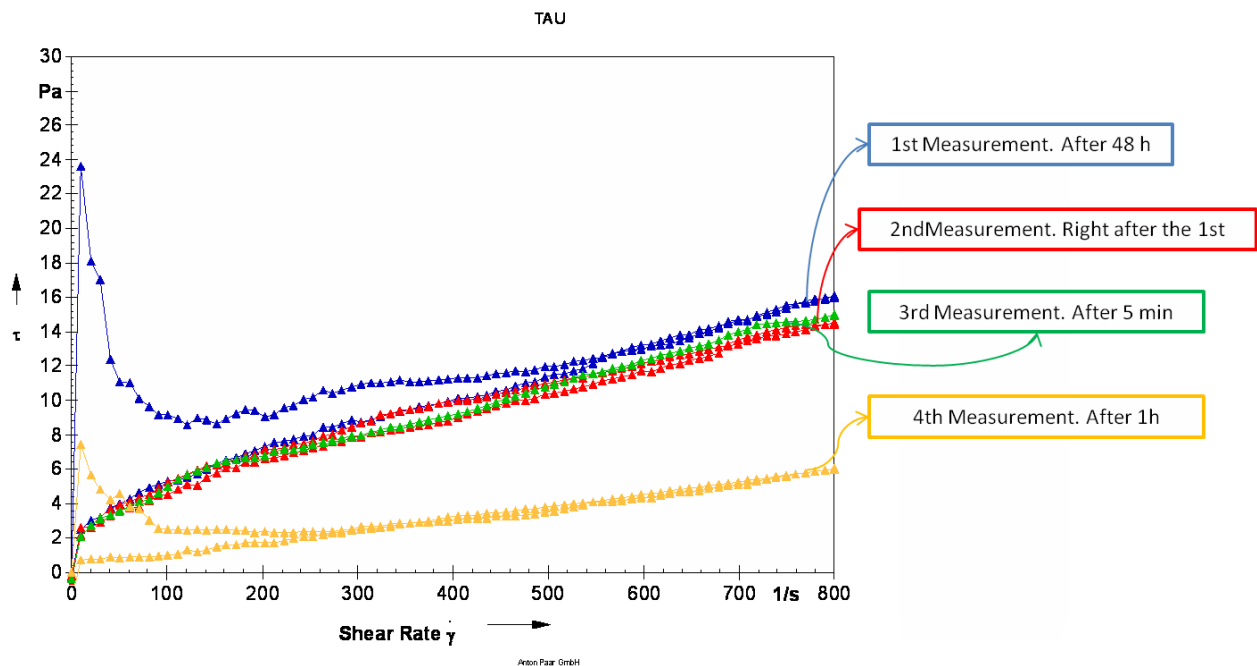


Fig. 5. Rheogram – shear stress (τ ; Pa) vs shear rate ($\dot{\gamma}$; s^{-1}) of reactor B. Four measurements of the same sample were made after different sample resting times (1st \blacktriangle ; 2nd \blacktriangle ; 3rd \blacktriangle ; 4th \blacktriangle).

3.3 Mathematical modeling

Also, the Herschel-Bulkley model indicated that reactor fluid A performed as a pseudo-Newtonian fluid called Bingham plastic, since the yield stress-value was > 0 (0.24 Pa) and a flow behaviour index of 1.06 (Table 4). Results obtained by the Ostwald and Bingham models confirmed a Bingham plastic behaviour of reactor A. However, since the τ_0 -value was almost 0 and the n -value 1 it was also closely performing as a Newtonian fluid which is consistent with the flow curve appearance (Fig. 2). However, when studying the viscosity curve (Fig. 4) the results showed an initial viscosity decrease and then a constant viscosity indicating a pseudo-Newtonian fluid behaviour.

The Herschel-Bulkley and Ostwald models both indicated a pseudoplastic behaviour of reactor D, since the τ_0 -value was 0 and $n < 1$ (Table 4). The Bingham model gave a yield stress of 0.33 Pa which did not indicate Newtonian or Bingham plastic behaviour. Thus, the common results for reactor D strongest indicate a pseudoplastic fluid behaviour.

Reactor B was hard to define also when modelling the rheogram data values of figure 4. The regression values were low for all three mathematical models (Table 4). However, the Herschel-Bulkely model had a flow behaviour index $n > 1$ indicating that the fluid acted as a shear thickening (dilatant) fluid, but the Ostwald and Bingham models indicated pseudoplastic and Bingham plastic behaviours, respectively. When the static yield stress appeared in the reactor B rheogram (Figures 2 and 4), the flow behaviour index showed shear thickening fluid behaviour ($n=3.4$) and a limit viscosity of 8 mPa*s. This also

corresponded to a low consistency value ($5 \cdot 10^{-10}$). At the static yield stress of 24 Pa (Fig. 5), the flow behaviour index showed shear thickening fluid behaviour ($n=1.41$) and a limit viscosity of 22 mPa*s. This also corresponded to a low consistency value ($5 \cdot 10^{-4}$). As soon as the fluid was measured again, n decreased (0.70) showing a pseudoplastic behaviour and K increased (0.11) indicating that the consistency of the reactor material was higher. The limit viscosity was 17 mPa*s. These results showing a time dependency and structure recovery strengthen the arguments for a thixotropic fluid behaviour of reactor B. Once the stirring has ended and the fluid was at rest, the fluid structure starts to rebuild. Therefore, the viscosity become time dependent. This information is important to consider for biogas reactor performance, e.g. when applying semi-continuous mixing.

	Herschel-Bulkley				Ostwald			Bingham	
	τ_0	n	K	R^2	n	K	R^2	τ_0	R^2
A	0.24	1.06	0.003	0.93	0.69	0.35	0.84	0.21	0.92
B	2.57	3.40	$5 \cdot 10^{-10}$	0.45	0.08	2.28	0.002	1.88	0.12
C	2.89	0.59	0.42	0.99	0.44	1.23	0.99	6.36	0.95
D	0	0.65	0.04	0.88	0.64	0.04	0.87	0.33	0.95
E	2.38	0.49	0.98	0.96	0.39	1.98	0.96	8.31	0.91

Table 4. The results obtained from mathematical modelling of rheogram data of fluids from reactors A–E. τ_0 : yield stress (Pa); n : flow behaviour index; K : Consistency index; R^2 : regression coefficient.

Also, fluids from reactor C and E were hard to define from modelling of the rheogram data because they gave indications for fluids being between pseudoplastic and Bingham plastic behaviours, i.e. the τ_0 -values were >0 (2.89 and 2.38) and $n < 1$ (Table 4).

4. Conclusion

The biogas reactor fluids investigated were behaving viscoplastically, since they had yield stress and one of them was also thixotropic, due to its partial structure recovering. However, the reactor treating slaughterhouse waste was very close to act as a Newtonian fluid. Also, there was a difference in dynamic- and limit viscosities depending on the substrates used. The results demonstrated that similar TS values did not necessarily correspond to similar flow and viscosity behaviours. Nor, did biosludge from two different Swedish paper mill industries with similar TS show similar viscosity values.

To encounter problems related to involvement of new substrates and/or co-digestions in existing facilities, investigations for possible viscosity changes are needed. Ongoing research will hopefully provide an important basis for predictions of changes in rheology linked to the composition of the organic materials, which are translated in the process. This is important in order to achieve proper designs in relation to possible variation in substrate mixes in conjunction with new constructions, but also to better control material flows in the existing facilities to avoid disturbances in the reactor performance.

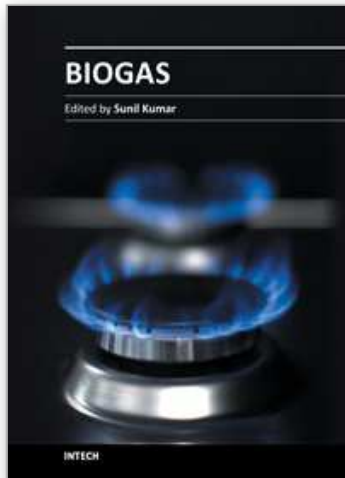
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Biogas

Edited by Dr. Sunil Kumar

ISBN 978-953-51-0204-5

Hard cover, 408 pages

Publisher InTech

Published online 14, March, 2012

Published in print edition March, 2012

This book contains research on the chemistry of each step of biogas generation, along with engineering principles and practices, feasibility of biogas production in processing technologies, especially anaerobic digestion of waste and gas production system, its modeling, kinetics along with other associated aspects, utilization and purification of biogas, economy and energy issues, pipe design for biogas energy, microbiological aspects, phyto-fermentation, biogas plant constructions, assessment of ecological potential, biogas generation from sludge, rheological characterization, etc.

How to reference

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Annika Björn, Paula Segura de La Monja, Anna Karlsson, Jörgen Ejlertsson and Bo H. Svensson (2012). Rheological Characterization, Biogas, Dr. Sunil Kumar (Ed.), ISBN: 978-953-51-0204-5, InTech, Available from: <http://www.intechopen.com/books/biogas/rheological-characterization>

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