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Development of an in-line process viscometer for the full-scale biogas process



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HIGHLIGHTS

- Full-scale measurement of the rheological properties of biogas slurry.
- Feedstock and TS-content of the slurry have a large impact to the viscosity.
- Mechanical disintegration improves the flow behavior of biogas slurry.

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ABSTRACT

An in-line viscometer was developed to determine the rheological properties of biogas slurries at a full-scale biogas plant. This type of viscometer allows the investigation of flow characteristics without additional pretreatment and has many advantageous aspects in contrast to the rotational viscometer. Various effects were studied: alterations in the feedstock structure, increasing total solid (TS) of the slurry and the disintegration of the feedstock on the rheological properties. The results indicate that the Power-Law model is sufficient for the description of the flow curve of biogas slurries. Furthermore, the use of more fibrous materials increases in viscosity. The increase in TS of 10.1–15.1% resulted in a sharp increase of the viscosity. The mechanical disintegration of the feedstock positively influenced the rheological properties, but the effects were more apparent at higher TS.

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1. Introduction

Biogas is known to be a versatile resource with many advantageous aspects for a future, environmentally friendly energy supply. The anaerobic conversion of organic materials like energy crops, manure and waste can replace fossil fuels for heat and energy production and can be used, after proper upgrading, as vehicle fuel. A major drawback is that the background for the design and dimensioning of agricultural biogas plants is mostly adapted from the manure and wastewater treatment sector (Weiland, 2006). The common digester design in agricultural biogas plants is the continuous stirred tank reactor (CSTR). These techniques are widely used for the anaerobic handling of liquid fluids with a low fiber content. The modifications for the digestion of crop materials are generally based on the empirical knowledge of the constructing engineer and on experiences with existing biogas plants. Formal research to

improve these techniques has not been conducted, because it is too time-consuming for this agile market (Lindorfer et al., 2008). However, the increasing utilization of arable land for biogas production raises ethical questions about using agricultural products as food or fuel. Therefore, industry professionals have increased interest in the use of residuals and wastes as input substrates, which have higher solid and fiber contents than plant feedstock (Menardo and Balsari, 2012). In general, the digestion of this kind of feedstock in agricultural biogas plants is crucial (Kusch et al., 2011) and will result in procedural problems in the digestion system (Hashimoto, 1983). Mixing is necessary for the uniform distribution of solids and fresh materials, enables contact to the microorganisms and is mandatory to ensure constant processing temperature in the reactor. Additionally, an appropriate mixing prevents the formation of floating layers, superficial incrustations or the sedimentation of small particles. It is also essential for the disposal of biogas from the slurry and thereby avoids the swelling of the digester content (Brehmer et al., 2012; Ward et al., 2008; Wu, 2010). To agitate the digester content several systems are available: external pumped recirculation, internal gas mixing and

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mechanical mixing systems. The latter is most commonly applied in agricultural biogas plants (Appels et al., 2008; Weiland, 2010). A previous study showed that agitation consumes the highest amount of energy in common biogas plants (Naegel et al., 2012) but by adjusting the mixing intensity, the energy demand can be reduced up to 70% without a loss in mixing quality (Lemmer et al., 2013). Therefore, the prediction of the optimum mixing intensity for a stable biogas process is essential for further development and improvement of the digestion technology. According to O'Neil (1985) and Vesvikar et al. (2005), rheological properties are crucial for an optimal design, control and operation of biogas plants. The rheological properties of manure and sludge from wastewater treatment are well known, but only very little data on the rheological properties of biogas slurry are available (Baudez et al., 2011).

For simplification, biogas slurry can be classified as a water-based suspension containing particles, fibrous materials, microorganisms and gas bubbles showing a shear-thinning non-Newtonian flow behavior. This means that the viscosity of the slurry decreases with increasing shear rate (Baroutian et al., 2013). Furthermore, it was found by Nges et al. (2012) that the viscosity of the biogas slurry is time dependent, with the tendency to built-up network structures once no shear stress occurs. The rheological properties of the slurry mainly depend on temperature, total solid (TS) content, particle size and shape, and dispersed gas bubbles.

To determine the rheological properties via the apparent viscosity, rotational and tubular viscometers are described in the literature (Ratkovich et al., 2013). Both systems have advantages and disadvantages for the rheological characterization of fluids. The advantages of the rotational viscometers are its simple handling, as well as its widely spread and highly reproducible measurements with small sample sizes. However, the measuring gap is very small and unsuitable for substrates with larger particles or it requires an additional pretreatment step such as sieving. On the contrary, with reference to tubular viscometers, the determination of the pressure drop in a tube with a defined length offers a simple and robust method for viscosity measurements and can be easily implemented. Based on the design of the tube viscometer, no further particle size reduction is required and a large and representative sample volume can be analyzed. Its integration into the process prevents degradation or changes in substrate structure during the transportation of the sample to the measurement device in the laboratory (Dieudé-Fauvel et al., 2014). Furthermore, the tube viscometer is a versatile and reliable instrument to analyze the rheological properties in research and industrial processes (Eshtiaghi et al., 2013). There is a general consensus that the knowledge of the rheological behavior and properties is an essential part of the process optimization, but little data are available.

Therefore, the aim of this work was to develop an inline tube viscometer for the monitoring of the rheological properties at the research biogas plant of the University of Hohenheim. The effects of changes in the feedstock composition, varying TS-contents of the digester slurries and the mechanical pretreatment of the feedstock were investigated.

2. Methods

The biogas plant of the University of Hohenheim is located at the agricultural research station "Unterer Lindenhof" near Reutlingen, Germany and was designed and built for full-scale studies and for the up-scaling of laboratory expertise (Fig. 1). The plant consists of two main digesters and one secondary digester. Each digester has a diameter of 14 m and a height of 6 m and is operated as CSTR with a working volume of 800 m³. The process temperature is set

to 40.5 °C. The main digesters are equipped with a concrete roof and the second digester is set up with a foil inflation dome for the gas storage. For the agitation of the slurries, a submersible motor mixer (Type 4670, ITT Flygt AB, Sweden) is installed in each digester. Because it is fed with fresh substrate, which has a higher mixing demand, digester 1 is equipped with one inclined shaft propeller mixer (Type Biogator HPR I, REMA, Germany) while digester 2 has a paddle inclined agitator (Type Biobull, Envicon, Germany). For solid substrate feeding every main digester has its own feeding system, consisting of a vertical mixer and feeding screws. For the additional pretreatment of the solid feedstock, a cross-flow grinder (Type Bio-QZ, MeWa, Germany) was installed between the vertical mixer and digester 1. To process of liquid manure and the slurries, a central pump station with a frequency-controlled eccentric screw pump (Type KL65 S, Wangen, Germany) was installed. The central pump station is equipped with a distribution manifold at the pressure and suction side. The outgoing pipes from the pressure side with a dimension of DN 150 open into the digester near the solid input at a height of 4 m. To avoid short circuits, the outgoing section of the DN 200 suction pipes is located on the opposite side of the reactor at a height of 0.35 m. The delivery rate of the liquid substrates is measured with an electromagnetic flow measuring system (Type Promag 50 W, Endress+Hauser, Suisse).

A pipe viscometer was developed to determine the rheological properties of the reactor slurries without time-dependent changes or further pretreatment (Fig. 2). This principle is based on the measurement of the pressure drop at a defined flow rate along a defined tube length. The pipe viscometer at the research biogas plant is located in an additional circuit directly behind the central pump and flow meter. The pipe viscometer consists of two difference pressure sections with a diameter of DN 100 and DN 80. The different tube diameters allow measurements in a shear rate range from 5 to 220 1/s by varying the flow rate of the eccentric screw pump. The length of the DN 80 section is 3.9 m and the DN 100 section is 4.1 m. At the beginning and end of the measurement sections, a diaphragm in-line seal (TYPE 981.10, WIKA, Germany) was integrated. For each measurement section, the diaphragm seals were connected to a differential pressure transmitter (Type DPT-10, WIKA, Germany). To avoid misinterpretations or temperature effects to the measurements, the substrate temperature at the rear part of the viscometer was determined. All data were collected and saved in the system control unit.

To determine the rheological properties it was necessary to calculate the apparent viscosity (η_{app}) in [Pa s], the apparent shear stress (τ_{app}) in [Pa] and the apparent shear rate ($\dot{\gamma}_{app}$) in [1/s] from the measurement data. The calculations were done according to Adhikari and Jindal (2001) and Slatter (1997) and are based on the following equations:

$$\dot{\gamma}_{app} = \frac{\dot{V}}{r} \quad (1)$$

$$\tau_{app} = \frac{\pi \cdot \Delta p \cdot r}{8 \cdot L} \quad (2)$$

Combining both leads to the apparent viscosity,

$$\eta_{app} = \frac{\tau_{app}}{\dot{\gamma}_{app}} = \frac{\pi \cdot \Delta p \cdot r^4}{8 \cdot L \cdot \dot{V}} \quad (3)$$

where $\dot{V}$ is the volumetric flow [m³/s], r the inner radius of the pipe [m], Δp the difference pressure [Pa] and L the length of the section [m].

The modeling of the flow curves were conducted with the power law model according to Ostwald-de Waele:

$$\eta_{app} = k \cdot \dot{\gamma}^{(n-1)} \quad (4)$$

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