Contents lists available at ScienceDirect

Chemical Engineering Research and Design

journal homepage: www.elsevier.com/locate/cherd

Rheological characterization of raw and anaerobically digested cow slurry

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ARTICLE INFO

Article history:
Received 12 September 2016
Received in revised form 17 December 2016
Accepted 4 January 2017
Available online 11 January 2017

Keywords:
Anaerobic digestion
Manure
Mixer-type rheometer
Rheology
Slurry

ABSTRACT

This study investigates the rheological properties of raw and anaerobically digested cow slurries. Measurements were carried out using a mixer-type rheometer (equipped with a helical ribbon) since this technique is believed to be more appropriate than conventional geometries when dealing with such heterogeneous fluids. Results revealed that slurries are very viscous (e.g. the zero shear rate viscosity of raw slurry at 37 °C is greater than 10^4 Pa s^n), and exhibit pronounced shear-thinning behaviors (flow index ranging between 0.15 and 0.6) and negligible yield stresses. Anaerobic digestion was shown to reduce the slurry apparent viscosity as well as its non-Newtonian character. It has been demonstrated that sieving may lead to a significant decrease of the slurry apparent viscosity, which suggests that literature results are relatively imprecise (since literature studies generally consider sieved samples). Results presented in this paper are important to enable better designs of anaerobic digestion reactors and equipment, especially when a computational fluid dynamics modeling approach is to be used.

1. Introduction

Anaerobic digestion is an attractive bioprocess that allows efficient management and valorization of livestock wastes. Animals' slurry is fed into an anaerobic digester, where in absence of oxygen, the organic matter is degraded by an extremely diverse microflora. These complex biochemical reactions produce biogas which is a mixture of methane (about 60%), carbon dioxide (around 40%) and traces of other gases. Anaerobic digestion provides several benefits among which: (1) Biogas is a renewable energy source. In large-scale plants, it is frequently burned in-site in a cogeneration unit to produce electricity for sale and thermal energy which is used to heat the digester and the farm's and livestock's buildings. (2) The digestate, i.e. the residual liquid phase, has a good fertilization potential. (3) Anaerobic digestion stabilizes the slurry, which greatly reduces its emissions to the environment (odor, greenhouse gases, etc). (4) Biogas constitutes a decentralized alternative energy source that is particularly appropriate for rural zones in developing countries (Perrigault et al., 2012).

In most industrial-scale digesters, a heat exchanger and a mixing system are employed to warm up and stir the digestate respectively, in order to enhance and improve the biogas yield. The heat exchanger is used to maintain the operating temperature around 37 °C (mesophilic process) or around 55 °C (thermophilic process). Heat is generally provided by the cogeneration unit.

In anaerobic digesters, some mixing of the liquid phase may occur thanks to the rising biogas bubbles, or to thermally-driven natural convection (resulting from the local heating by the heat exchanger which may lead to an unstable density stratification). However, such low-mixing levels are often far from being sufficient, especially that the digestate apparent viscosity is generally very important (Mbaye et al., 2014). Therefore, mixing devices are generally used in industrial-scale digesters, including mechanical, hydraulic and pneumatic mixing systems (Lindmark et al., 2014).

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http://dx.doi.org/10.1016/j.cherd.2017.01.005

An efficient stirring of the digestate is necessary to avoid significant gradients of nutrient concentrations, inhibitory substances, biomass and suspended solids, as well as gradients of temperature and pH. Moreover, it also minimizes heavy solids sedimentation, reduces the formation of floating scum or straw blankets, promotes the rise of biogas bubbles, increases the heat transfer efficiency with the heat exchanger and enhances liquid-to-bacterial cells and liquid-to-biogas bubbles mass transfer rates, etc. The reader may refer to the literature survey by Lindmark et al. (2014) on the effects of mixing on anaerobic digestion.

Cost-effectiveness studies for agricultural anaerobic digesters should account for charges related to the slurry handling and processing (e.g. pumping, pre-heating prior to introduction into the reactor), to the process operation (e.g. stirring, pumping in the case of a hydraulic mixing system, heating) and to the digestate handling (e.g. pumping, dewatering); therefore, the knowledge of the rheological properties of raw and anaerobically digested slurries is of utmost importance. Indeed, the efficiency and the power requirements of these unit-operations are closely linked to the rheological behavior of the manipulated fluids. Moreover, reliable data on the rheology of raw and anaerobically digested slurry are necessary for determining the type, capacity and optimal design of the process equipment such as the agitator, heat exchanger(s), pump(s), dewatering material and piping systems.

Nonetheless, very few studies have addressed the rheological characterization of raw and anaerobically digested slurries. Indeed, as discussed in Section 2, these fluids contain large 'particles' such as pieces of stem and straw, which presence constitutes an issue for rheological measurements. Therefore, these literature studies (Chen, 1986a, 1986b; Achkari-Begdouri and Goodrich, 1992) have considered sieved slurries. However, as shown later in this paper, sieving may dramatically affect the sample apparent viscosity measurement.

In an attempt to overcome this lack in literature data, this article addresses the steady-state rheological properties of raw and anaerobically digested cow slurries. However, the properties of slurry are expected to depend on the cattle race and diet, etc. Therefore, the rheological data reported in this paper mainly aim at providing a reliable assessment of the rheological properties of slurries (e.g. ranges of variation of the flow index and order of magnitude of the zero shear rate viscosity) rather than a very accurate description of the rheology of the particular slurry that has been considered. Moreover, since literature studies have dealt with sieved slurry, experiments have been performed using sieved and non-sieved slurry samples to determine whether sieving has an important effect or not on the slurry rheology.

Measurements were carried out using a helical ribbon rheometer. Indeed, as explained later (see Section 3.5), this technique is believed to be more appropriate than conventional rheometers when dealing with such heterogeneous fluids; thus, it is expected to provide reliable information on their viscous characteristics.

Rheological data presented in this paper are important to enable better designs of anaerobic digestion reactors and equipment. Moreover, the digestate rheological properties are a necessary input for computational fluid dynamics (CFD) modeling which is increasingly used to characterize the hydrodynamics, heat and mass transfer in anaerobic digesters (Craig et al., 2013; Yu et al., 2013; Wu, 2014; Lindmark et al., 2014). The slurry thermal properties are also often required in CFD studies. However, to the authors' knowledge, such data have not been reported so far in the literature. Therefore, slurry heat capacity and thermal effusivity measurements were also conducted in this paper.

2. Literature survey

2.1. Rheology of raw slurry

Cattle slurry contains pieces of stems and straw and hair (and possibly bedding material and dirt) reaching several centimeters in length. Stems and straw originate from fodder that has not been completely decomposed in the animal digestion system. The presence of such large 'particles' constitutes an issue for rheological characterization. Indeed, classic rotational and pipe rheometers are generally designed with narrow gaps and diameters respectively. However, for reliable measurements, the particles should be homogenously distributed within the sample, i.e. their size should be small compared to the apparatus gap/diameter (Schramm, 2000). Thus, this condition is generally unfulfilled when dealing with slurries. For example, long pieces of straw will be necessarily oriented vertically in a narrow gap rotational rheometer, which is expected to alter the measurements accuracy and reliability.

Thereby, to be able to perform correct measurements, Chen (1986a, 1986b) considered sieving the cattle slurry using a 2 mm opening sieve in order to remove coarse 'particles'. However, it is noteworthy that sieving using such a fine mesh may dramatically affect the sample apparent viscosity as shown later in this paper. Results acquired using a rotational rheometer and a tube viscosimeter were similar with the exception of highly diluted slurries (total solid content (TSC) below 3%), a fact that was attributed to solids settling in the rotational rheometer. Achkari-Begdouri and Goodrich (1992) considered a coarsely sieved cattle slurry with a 1 cm screen, but their measurements were performed in a 1.2 mm gap rheometer. El-Mashad et al. (2005) conducted rheological measurements of non-sieved dairy cow slurry in a narrow gap rheometer (its width was not specified). However, the accuracy of the results reported in these two papers is expected to be altered by the presence of large particles as explained before.

Chen (1986a, 1986b) dealt with a slurry having a 19.3% TSC. The effects of solids content on the rheology were investigated by considering samples diluted with water down to a 2.8% TSC. Likewise, Achkari-Begdouri and Goodrich (1992) studied samples which TSC ranged between 2.5 to 12%, while El-Mashad et al. (2005) considered slurries having a TSC around 10%. These authors agreed that slurries behave as a shear-thinning fluid exhibiting a negligible yield stress. However, while Achkari-Begdouri and Goodrich (1992) and El-Mashad et al. (2005) reported that the slurry rheology can be accurately described by the power law, Chen (1986a, 1986b) has found that this model does not hold for TSCs greater than 3%.

Chen (1986a, 1986b) and Achkari-Begdouri and Goodrich (1992) showed that the apparent viscosity and the consistency index of the slurry increase with its TSC. However, while Chen (1986a, 1986b) reported that the flow index is nearly independent of the TSC, Achkari-Begdouri and Goodrich (1992) have found that this coefficient decreases when the total solid content is increased, which indicates that the non-Newtonian behavior becomes more important.

All of the four studies dealing with the rheology of raw slurry have found that its apparent viscosity and consistency index decrease when the temperature is increased. However, while Chen (1986a, 1986b) and El-Mashad et al. (2005) reported that the flow index is nearly independent of the temperature, Achkari-Begdouri and Goodrich (1992) have found that this coefficient increases toward one when the temperature is increased, which indicates that the slurry behavior becomes more Newtonian.

Finally, it could be noted that the divergence in the literature results is probably due to the variability in the characteristics of the slurry which depend on the cattle race and diet, time of the year and the presence of dirt in the samples, etc. However, it is also likely that the results are affected by the sieving fineness and by experimental errors, e.g. those