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Reducing agitation energy-consumption by improving rheological properties of corn stover substrate in anaerobic digestion

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HIGHLIGHTS

- Improving rheological properties was tried to reduce agitation energy-consumption.
- Size-reduction & temperature-increase reduced shear stress by 10.4% & 11.7%.
- 9.2% P_{TS}-reduction was achieved by size-reduction from 20 to 80-mesh at 35 °C.
- 10.3%/10 °C P_{TS}-reduction was achieved at 20-mesh compared with 9.0%/10 °C at 80-mesh.

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ABSTRACT

Rheological properties of corn stover substrate were investigated to explore agitation energy reduction potential for different total solid (TS) in anaerobic digestion. The effects of particle size and temperature on rheological properties and corresponding energy reduction were studied. The results indicated that corn stover slurry exhibited pseudo-plastic flow behavior at TS of 4.23–7.32%, and was well described by Power-law model. At TS of 4.23%, rheological properties were not obviously affected by particle size and temperature. However, when TS was increased to 7.32%, there was 10.37% shear stress reduction by size-reduction from 20 to 80-mesh, and 11.73% shear stress reduction by temperature-increase from 25 to 55 °C. P_{TS} was advanced as variations of power consumption by TS-increase from 4.23% to 7.32%. There was 9.2% P_{TS}-reduction by size-reduction from 20 to 80-mesh at 35 °C. Moreover, P_{TS}-reduction of 10.3%/10 °C was achieved at 20-mesh compared with 9.0%/10 °C at 80-mesh.

1. Introduction

The anaerobic digestion of lignocellulosic biomass is an important way to dispose agricultural residues for obtaining clean energy of biomethane. At present, anaerobic digestion of crop stalks has been paid increasing attention in China, as large amount of crop stalks such as corn stover and wheat straw is generated annually (Pang et al., 2008), serious hazy weather frequently appeared in many areas resulting from the open-field burning of crop stalks. Compared to the widely-used substrates of animal manures and food wastes with good fluidity and biodegradability, crop stalks are hard to be anaerobically converted to biogas because the complex chemical structure of lignocelluloses seriously hinders the effective conversion of the biomass to biogas (Shen et al., 2013). In addition, crop stalks are kinds of heterogeneous substrates with specific physical properties of heterogeneity, low density, and high water-holding capacity. Crop stalks normally need to be ground before put into digester. The ground crop stalks could not be evenly distributed inside of digester, some of them would always float on the top of digester, leading to poor heat and mass transfer and low biogas yield.

Mixing is very important to solve above problems for effective anaerobic digestion of lignocellulosic crop stalks, as the improvement on mixing could greatly improve anaerobic digestion performances and enhance biomethane production correspondingly (Shen et al., 2013; Smith et al., 1996). Generally, mixing can be achieved by a few ways, including gas recirculation, mechanical pumping, and mechanical stirring (Karim et al., 2005). Mechanical stirring can easily achieve homogenization of substrates in digester and thereby is widely applied in industrial operations involving various solid-liquid flows (Bridgeman, 2012; Ghanimeh et al., 2012; Kowalczyk et al., 2013). Therefore, mechanical stirring is normally employed for mixing substrates of crop stalks, especially, when the total solid (TS) in the slurry is relatively high (Ward et al.,

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2008). It is a big challenge to well mix substrate slurry while using energy as less as possible. This has specific economic meaning for large-scale biogas plants using crop stalks as substrates, in which energy consumption for mixing often accounts for large fraction of total energy consumption.

There are a number of methods to improve mixing energy efficiency. Improving rheological property of substrate would be one of options. Undoubtedly, the apparent viscosities of lignocellulosic biomass slurries in the anaerobic digestion would be increased when biomass TS was at higher level (Knutsen and Liberatore, 2010; Viamajala et al., 2009; Wiman et al., 2011). Correspondingly, more energy for mixing needs to be employed. Reduction of substrate particle size would reduce apparent viscosity of corn stover and red-oak sawdust during the saccharification for ethanol production, resulting in more than 50% improvement on enzymatic hydrolysis (Dasari and Berson, 2007; Viamajala et al., 2009). Besides, the temperature during the digestion also closely related to the flow behaviors of lignocellulosic biomass slurries. Typical rheological properties of manures, including consistency coefficient (K) and apparent viscosity (μ), presented the negative correlations with digestion temperature (El-Mashad et al., 2005). Thus, improving the rheological properties of the lignocellulosic biomass slurry can be a possible way to promote the anaerobic digestion performances and optimize the energy input for the mixing (Carreau et al., 1993). However, the related work currently is scarcely investigated for the anaerobic digestion of corn stover.

In this work, a typical lignocellulosic biomass of corn stover was used as the model substrate for anaerobic digestion with mechanical stirring. The basic rheological properties of corn stover slurries were measured at different TS contents while increasing the substrate loading concentration. The flow behaviors of corn stover slurries were also investigated at various particle sizes and digestion temperatures, and the theoretic watts for mechanical stirring was calculated to explore the potential of agitation energy-reduction by improving the rheological properties.

2. Methods

2.1. Corn stover

Corn stover was collected in fall of 2012 from the farm near Beijing city in China. The corn stover was air-dried after the indigestible materials were picked out. It was chopped into 1.0–1.5 cm in length. According to the published work, the chopped corn stover was pretreated by 2% NaOH for the digestion (Zheng et al., 2009). Afterwards, the pretreated corn stover was washed by tap water and filtered. The washed substrates were air-dried and ground into the intended particle sizes (see Table 1) with a lab-scale mill. The ground corn stover was used for particle size analysis and digestion.

2.2. Anaerobic digestion

Anaerobic digestion of corn stover was carried out in sequencing mode in three continuously stirred tank reactors (CSTR) (10.0 L) with working volume of 8.0 L. The temperature and the pH were maintained at 35 ± 2 °C and 6.8–7.2, respectively. These three CSTRs were fed by the pretreated corn stover with particle sizes of 5, 20 and 80-mesh, respectively. The substrate loading concentration and the seeding sludge inoculation were 50 and 15 g L^{-1} for the start-up, in which the sludge was taken from an anaerobic digester for manure in Nanwu, Beijing, China. After 20 days start-up, the CSTRs were fed manually every 24 ± 1 h. In order to increase the TS of corn stover slurry in digester, the substrate loading concentration was increased from 65 to 95 g L^{-1} in three CSTRs (See Table 1). The digestion was run for a hydraulic retention time (HRT) of 45 days at each loading concentration. The corn stover slurry (effluent) was collected after feeding for viscosity determination with the intervals of 15 days. The reported results of viscosity were the average of three determinations during these 45 days. Similar processes were also performed at 25 ± 2 and 55 ± 2 °C to investigate the corresponding rheological properties. During the digestion process, the agitation for the mixing was achieved by a top-mounted motor with the stirring rate of 80 rpm, and the frequency was controlled as 12 times per day and lasted for 5 min for each stirring (Shen et al., 2013).

Table 1
The employed substrate loading concentration, particle size and temperature.

Items	Low	Medium	High
Substrate loading concentration/g L^{-1}	65	80	95
Particle size/mesh	80	20	5
Temperature/°C	25	35	55

2.3. Analytical methods

Rheological properties, including the apparent viscosity, shear stress, shear rate, and torque, were measured using a viscometer (LVDVII+ pro, Brookfield Engineering Laboratories Inc., USA) integrated with a small sample adapter, SC4-31 spindle and SC4-31/13R spindle chamber (Brookfield Engineering Laboratories Inc., USA). Data were collected by a computer integrating with the software of Rheocalc (Ver. 3.0, Brookfield Engineering Laboratories Inc., USA).The torque was controlled within the range of 0.0007–0.06 mN m, which was specified by the viscometer manufacture. When rheological properties at different temperatures were considered (see Table 1), the temperature for the determinations was controlled by a water bath at the temperature of 25, 35, and 55 °C, respectively.

TS and density of the corn stover slurries were measured according to the standard methods (APHA, 1998). The particle size distribution of the ground corn stover was obtained by a particle size analyzer (EanoZS, Malvern Instruments, UK).

2.4. Calculation of power consumption

The employed CSTR without baffles was a cylindrical flat-bottomed bioreactor with 0.2 m in diameter of 0.32 m in height. The height from the liquid surface to reactor bottom was 0.26 m. A motor was mounted on the top of CSTR to drive a vertical shaft with three layers pitched blades. The diameter, width and angle of each pitched blade were 0.17 m, 0.04 m and 45°, respectively.

The power number (N_p) of the agitator was calculated based on the following equations (Eqs. (1)–(4)) (Nagata, 1975):

$$N_p = \frac{A}{R_e} + B\left[\frac{1000 + 1.2Re^{0.66}}{1000 + 3.2Re^{0.66}}\right]^q \left[\frac{H}{D}\right]^{(0.35+b/D)} (sin\theta)^{1.2} \quad (1)$$

$$A = 14 + \left(\frac{b}{D}\right)\left[670\left(\frac{d}{D} - 0.6\right)^2 + 185\right] \quad (2)$$

$$B = 10^{\left[1.3-4\left(\frac{b}{D}-0.5\right)^2-1.14\left(\frac{d}{D}\right)\right]} \quad (3)$$

$$q = 1.1 + 4\left(\frac{b}{D}\right) - 2.5\left(\frac{d}{D} - 0.5\right)^2 - 7\left(\frac{b}{D}\right)^4 \quad (4)$$

where, R_e is Reynolds number; H is height from liquid surface to reactor bottom; D is diameter of vessel; θ is angle of pitched blade; b is width of pitched blade; d is diameter of pitched blade.