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Rheological behavior of the sludge in a long-running anaerobic digestor: Essential factors to optimize the operation

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ABSTRACT

This work investigated the rheological behavior of sludge in a long-running digestor and established a timely approach for monitoring the torque information of an anaerobic process. With multi-methods, the rheological behavior of sludge within the digestor were revealed, which indicated that: (1) the on-line torque sensing approach was an efficient method to obtain timely torque signals, which could give a reliable prediction to the variation in the rheological behavior of sludge, and further provide useful information to monitor the operation of an anaerobic digestor; (2) the thixotropic index of sludge in the digestor decreased continuously along with the operational time, which showed a weakening tendency in the interaction among sludge particles; (3) both the content of total suspended solids (TSS) and extracellular polymeric substances (EPS) had close relationships with the limit viscosity of sludge, but TSS showed a positive impact, while, the impact of EPS was negative.

1. Introduction

Anaerobic digestion (AD) is a traditional and effective approach to treat organic wastes and high-strength wastewater. Due to its attractive merits in bio-gas recovery and degradation of high concentration biomass, it is still an attractive approach in the related environmental engineering field. For reducing the space requirement, an anaerobic digestor is generally operated at high concentration of biomass, which determines the contained fluid within the digestor being a non-Newtonian fluid and exhibiting very special characteristics, for instance, variable viscosity, thixotropy, and at the same time manifesting a pseudo plastic behavior when being exerted an external shear force [1,2]. As a non-Newtonian fluid, the shear stress is not linearly proportional to the shear rate. Such a property actually has an important impact on the transfer of mass, energy and momentum, and totally determines the performance of a relevant bioreactor. Knowledge relating to the behavior of non-Newtonian fluid belongs to the science of rheology. In this meaning, the rheological behavior of sludge should be a primary aspect to be considered in the design, operation and management of an anaerobic digestor.

During a process of AD, organics are degraded by numerous anaerobic microorganisms, which cause the concentration and chemical composition of the organics changing constantly. Actually, in an anaerobic digestor, an AD process includes four major steps, and is a continuous process, during which the physico-chemical composition, microbial communities of sludge experiences continuous variations, they not only changes the microcosmic structure of sludge, but also heavily influences the macro rheological behavior of anaerobic activated sludge [3]. For example, the apparent viscosity, one important index to describe the rheological behavior of a non-Newtonian fluid, was found to be changed markedly during an AD process, which might mainly attribute to the changes of solids content. Additionally, Baudez et al. [4] measured the rheological behavior of the digested sludge at different concentrations, their results showed that the rheological behavior of digested sludge only depended on yield stress and Bingham viscosity, but nevertheless, both parameters had a close relationship with the solids content of sludge. Apart from these results, recent researches [5,6] also demonstrated that the composition, temperature, stirring intensity and particle size within an anaerobic digestor would influence the rheological properties of anaerobic digested sludge, which heavily changed the heat and mass transfer process, and further affected the stability of operation and the efficiency of bio-gas production.

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Table 1
Conditions of the water quality in influent at each operational stage.

Operational stage	COD (mg/L)	Organic loading rate (kg COD/m^3 d)	TN (mg/L)	TP (mg/L)
I (1–15 day)	2182.86 ± 93.88	1.09 ± 0.047	31.18 ± 1.34	6.24 ± 0.27
II (16–53 day)	2477.78 ± 91.61	1.24 ± 0.046	35.40 ± 1.31	7.08 ± 0.26
III (54–85 day)	2912.38 ± 102.71	1.46 ± 0.051	41.61 ± 1.47	8.32 ± 0.29
IV (86–105 day)	3979.05 ± 104.95	1.99 ± 0.053	56.84 ± 1.50	11.37 ± 0.30

In regards to the treatment of high-strength wastewater, an AD process is also applied extensively in this engineering field [7–9]. Comparing with a conventional aerobic treatment, the advantages of AD are very dominant, which includes reliable energy recovery, no aeration requirement, no oxygen transfer limit at high organic load rates and a low sludge production rate [10,11]. No matter for waste sludge digestion or high-strength wastewater treatment, the stability and continuity must be primary factors to be considered for the operation of digestor, which determines that a timely monitoring method is highly needed. Considering the high variability and sensitivity of an AD process, it might be the best option to adopt an on-line monitoring and controlling method based on the basic characteristics of the fluid within the bioreactor. So far, some methods have been tried to solve this problem. Multi-wavelength fluorometry was once examined for the on-line monitoring of an AD process [12], and the near infrared spectroscopy in online-monitoring of feeding substrate quality in an AD was also used for the same purpose [13]. Besides, other on-line estimation approaches were verified to be reliable in providing information towards the rapid on-line monitoring of AD processes [14], which could be used as a stand-alone and promising sensor device. However, as for the purpose of on-line monitoring and controlling, the researches performed to date have mainly focused on a single physical and chemical property as an indicator, rather than on a comprehensive index. On the contrary, as a macro and integrated property, the rheological characteristics were very convenient to be converted to an on-line signal and can achieve timely monitoring and controlling of the relevant process [15,16]. Actually, through an investigation on AD under high-solid contents, the rheological evolution of sludge was demonstrated to be a feasible method to monitor and control an AD process [17]. Thus, a real-time approach on the basis of rheological behavior is of primary importance to achieve an online monitoring and controlling an anaerobic digestor, which is beneficial to the stable operation of an AD process.

To the best of our knowledge, most of the literatures about the anaerobic sludge rheology have only focused on measuring the basic properties of the fluid in a digestor, including the total suspended solids (TSS), the surface charge and ionic strength of a bulk solution [18], the extracellular polymeric substances (EPS) content [6], and evaluating their influences on the rheological behaviors from a short-term viewpoint [1,2,17]. However, from a practical viewpoint, only the data obtained from a long-running anaerobic digestor can provide a useful and reliable indication as the reference for the subsequent investigation [19].

Based on the above analysis, this work aims at investigating the rheological behavior of sludge in a long-running anaerobic digestor and presenting a new approach to understand more about the rheological characteristics of the biomass. Therefore, two closely related aspects were mainly considered: (1) measuring the rheological characteristics of the sludge in anaerobic digestor and analyze their varying pattern over time from a long-term viewpoint; (2) establishing a real-time approach to monitor the same anaerobic digestor by using an on-line torque sensing system, and try to correlate the relationship between the timely torque signal and the rheological behavior. We hope the results would provide a useful reference to optimize the operation and management of an AD process.

2. Materials and methods

2.1. Sludge acclimation and experimental conditions

The raw sludge was obtained from the concentrated tank of Lijiao municipal wastewater treatment plant located at Haizhu District (Guangzhou, China). After being taken to the lab, the sludge was put in a container for two months without adding any nutrients, then, 18-L of this sludge with the concentration of 28 g/L TSS was added into a 32-L anaerobic digestor. The influent was prepared by mixing tap water with concentrated nutrient solutions (COD: N: P at 350:5:1). Other nutrients in the influent included: $NaHCO_3$: 660 mg/L, $MgSO_4$: 8 mg/L, NaCl: 120 mg/L, $CaCl_2$: 0.59 mg/L, $FeSO_4$: 5.53 mg/L, Na_2MoO_4: 0.0045 mg/L, H_3BO_3: 0.063 mg/L, $CoCl_2$: 0.48 mg/L, $CuCl_2$: 0.16 mg/L, $NiCl_2$: 0.65 mg/L, $ZnCl_2$: 0.67 mg/L, $MnCl_2$: 2.02 mg/L. Conditions of the water quality in the influent at every operational stage are shown in Table 1.

2.2. Schematic diagram and operational process

The experimental system included a dispensing system, a torque-sensing device and a PLC controller as well as a signal collecting computer. The anaerobic digestor had a 32-L operating volume with a spiral mixer submerged in the digestor and connected to a torque sensor. The torque sensor was connected to a data converting device, thus, the obtained data could be processed and stored automatically through an on-line approach. The schematic diagram is shown in Fig. 1. During the whole experimental period, no sludge was discharged except for sampling. The stirring speed was kept constant at 40 rpm, and the temperature in the digestor was kept at 35 ± 2 °C by a water bath with heating rods inside. The influent was injected into the reactor in a batch mode, and every two days, equal volume of supernatant was discharged. The detailed operating conditions are listed in Table 2.

The values of torque were automatically measured every 10 s by a torque sensor (WDH-5 GT, Wardline Inc., China), and stored by the connected computer. The torque value of each day was calculated their averaged value with the obtained data.

2.3. Rheological measurements and modeling

A viscometer with an ultra-low viscosity adapter (DV-III ULTRA, Brookfield, Massachusetts, USA) was used to carry out all rheological tests. The used viscometer was equipped with a sample cup and a rotor (304 # stainless steel). In each test, a 16-mL volume of sludge sample was put into the sample cup, and then, conducted the needed rheological tests with the following procedure: (1) measured the shear stress (τ) and the viscosity by increasing the shear rate (γ) from 10 s^{-1} to 300 s^{-1}, respectively, each datum was recorded every 10 s; (2) keeping the rotor speed at 250 rpm, then, measured the viscosity at the shear rate of 281.29 s^{-1} lasting for 30 min, each datum was recorded every 10 s, and then, the steady datum was termed as the limit viscosity [20]. The limit viscosity, defined as a constant value of the apparent viscosity of sludge subjecting to a shear rate lasting for a certain time period, was then used to characterize the rheological behavior of the sludge; (3) measured viscosity at the lowest speed (25 rpm) and the highest speed