Process Biochemistry 51 (2016) 345–351

Contents lists available at ScienceDirect

Process Biochemistry

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

Effect of hydrodynamic shear on biogas production and granule characteristics in a continuous stirred tank reactor

Jiankai Jiang[a,c], Jing Wu[b,**], Souhila Poncin[a], Huai Z. Li[a,*]

[a] Laboratory of Reactions and Process Engineering, Université de Lorraine, CNRS, 1, rue Grandville, BP 20451, 54001 Nancy cedex, France
[b] State Key Joint Laboratory of Environment Simulation and Pollution Control, School of Environment, Tsinghua University, Beijing 100084, China
[c] CAS Key Laboratory of Urban Pollutant Conversion, Department of Chemistry, University of Science & Technology of China, Hefei 230026, China

ARTICLE INFO

Article history:
Received 2 October 2015
Received in revised form 4 December 2015
Accepted 17 December 2015
Available online 24 December 2015

Keywords:
Anaerobic digestion
Hydrodynamics
Shear rate
Biogas production
CSTR

ABSTRACT

Hydrodynamic shear plays an essential role in the formation, structure, mass transfer, metabolism of microbial community, and consequently the performance of a bioreactor. The present work focuses on an original investigation to study the effect of hydrodynamic shear on the anaerobic biodegradation process in a continuous stirred tank reactor (CSTR) equipped with a helical ribbon. The classical Metzner–Otto method was adopted to estimate the mean shear rate and the particle image velocimetry (PIV) was applied to visualize the instantaneous velocity field in the reactor. A constant prefactor of 17.1 was obtained to compute the mean shear rate from the stirring speed of the helical ribbon. An optimal shear rate of 6.8 s^{-1} is obtained for a maximal biogas production rate. It is due to two antagonist mechanisms, namely the enhanced mass transfer and the structural change of granules. Intense hydrodynamic shear diminishes the methane content as a result of the accumulation of volatile fatty acids (VFAs). In addition, the noticeable deformation of granules is mainly due to the abrasion rather than compaction of granules. The density of granules remains unchanged while mechanical strength is slightly enhanced after the experiments.

1. Introduction

As an efficient and convenient approach, anaerobic digestion was widely applied to the wastewater treatment in the form of granule-based upflow anaerobic reactor such as upflow anaerobic sludge bed (UASB), expended granular sludge blanket (EGSB) and internal circulation (IC) anaerobic reactor [1,2]. The produced biogas is a kind of alternative energy which can be used for heat production, cogeneration and gas grid injection after suitable purification, as well as vehicle fuel with further compression [3,4].

The efficiency of anaerobic digestion including both biogas production and wastewater treatment depends to a large extent on the operating conditions, which is determined by several key parameters including organic loading, hydraulic retention time (HRT), solids retention time (SRT), temperature and pH [5–8]. The hydrodynamic conditions play an essential role in the formation, structure, mass transfer, and metabolism of microbial community [9]. As a key operating factor, it depends mainly on the hydraulic loading, biogas production rate and eventual circulation flow of effluent in the upflow anaerobic reactor. Compared with other representative parameters such as superficial liquid (or gas) velocity, Reynolds number, the mean shear rate exerted on granules is the most suitable parameter to reliably describe the local hydrodynamic conditions and to better understand the effect of hydrodynamic shear.

Up to now, the number of reported studies concerning the effect of hydrodynamic shear in anaerobic granular sludge reactors is still limited as compared with aerobic biofilm reactors [9]. In upflow anaerobic reactor, the mean shear rate was firstly estimated in the IC anaerobic reactor based on the energy dissipation, which was approximately twice as high as that in the UASB [10]. Then subsequent works adopting the same estimation method of mean shear rate were carried out to study its effect on the nucleation and disruption of granules [11–13]. The appropriate hydrodynamic shear contributed remarkably to the nucleation process [13], and granules could bear the high hydrodynamic shear only with low increase of shear rate [12]. Another method was also applied to estimate the hydrodynamic shear in a hybrid anaerobic reactor, which had a positive effect at low value, while a negative effect appeared at high value for the reactor performance [14]. Recently, the precise

* Corresponding author.
** Corresponding author.
E-mail addresses: wu_jing@tsinghua.edu.cn (J. Wu), Huai-Zhi.Li@univ-lorraine.fr (H.Z. Li).

http://dx.doi.org/10.1016/j.procbio.2015.12.014
1359-5113/

measurement of shear rate around a granule was realized with the aid of Particle Image Velocimetry (PIV) and micro-PIV [15,16].

The shear rate in an upflow anaerobic reactor is spatially heterogeneous owing to the random distribution of rising bubbles, which contributes considerably to the shear rate owing to their relative motion to liquid. Hence, it is difficult to obtain a steady shear rate in such a reactor. A CSTR equipped with a helical ribbon provides relatively stable mean shear rate and is suitable to stir shear sensitive matters as well [17,18]. As an efficient close-clearance impeller, the helical ribbon impeller is commonly applied to mix highly viscous fluids in chemical engineering [19]. Herein it is appropriate to theoretically study the effect of hydrodynamics on sludge granules. The effect of shear stemming from mixing in anaerobic digesters has been extensively studied for the treatment of municipal sludge, municipal solid waste and animal manure [20]. High mixing intensity could reduce particle size and diffusion limitation, this enhances then the processing capacity [21]. In contrast, several studies have shown that high mixing intensity resulted in a decline of digester performance, such as lower biogas production [22], operation instability [23]. Besides, other parameters might affect the effect of mixing intensity. Under steady state conditions, different mixing intensities had no effect on the biogas production rates, while intense mixing displayed a negative effect during initial start-up [24]. At high organic loading, intensive mixing gave rise to acidification and failure of the digester operation, while it had no significant effect at low organic loading [25]. In addition, Couette–Taylor reactor was used to study the influence of hydrodynamic shear on the detachment and physical properties of anaerobic biofilm [26,27]. To our best knowledge, the effect of hydrodynamic shear on anaerobic sludge granule characteristics and its biogas production process in a CSTR has not been yet reported in the literature.

The present work aims at investigating the effect of hydrodynamic shear on the biogas production process and the physical characteristics of granular sludge in a CSTR equipped with a helical ribbon. The classical Metzner–Otto method was adopted to quantify the mean shear rate, which defined that the effective shear rate was linearly related to the rotation speed of the impeller by a dimensionless constant in the laminar flow regime [28]. The instantaneous velocity field inside the reactor was acquired and analyzed by the PIV technique.

2. Materials and methods

2.1. Granular sludge

Anaerobic sludge granules were sampled from an EGSB reactor treating starch wastewater and cultured in glucose solution in the laboratory. The detailed substrate composition was described in the previous work [29].

The measurement of granule density was realized through a series of glycerol solutions with different densities, which were measured by densitometry in advance. The anaerobic granules were added into 100 mL graduated cylinders filled with different glycerol solutions. Under a quiescent condition, the granules moved up or down depending on the solution density. In a suitable solution, the granules suspended without sedimentation or flotation. Thus, the density of glycerol solution could be considered as that of the granule.

The mechanical resistance of a granule against an orthogonal compression was measured by a penetrometer (Instron, USA) equipped with a cylindrical needle (3 mm diameter) and a force sensor in the range of 0–10 N. Thirty randomly selected original granules and deformed granules after experiments were respectively measured to obtain a mean mechanical strength.

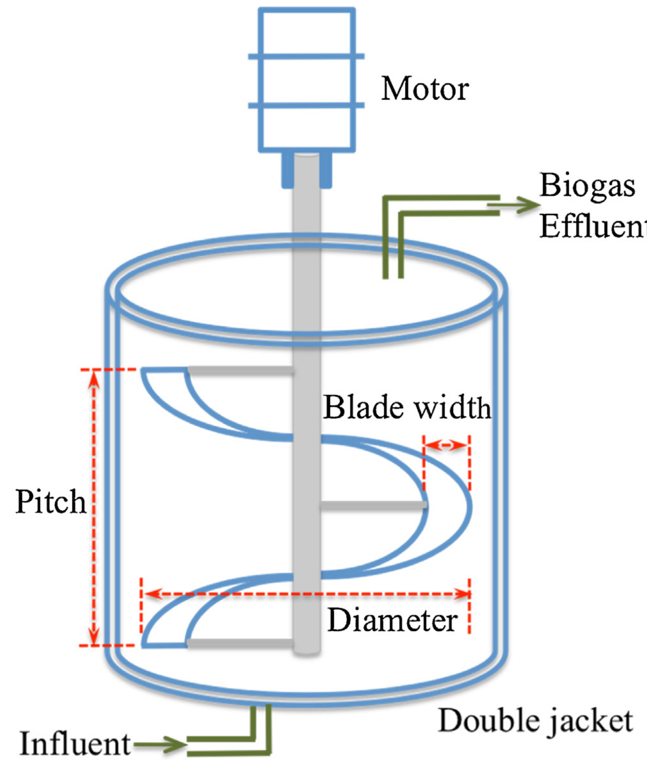

Fig. 1. Schematic of the CSTR system.

2.2. Experiments in a microreactor

An integral granule was placed in the center of a microreactor maintained at 35 °C and fed with above mentioned glucose solution (COD 3000 mg/L) that had been filtered through a microfiltration membrane to remove impurities. The microreactor was a parallelepiped cellule made of transparent Plexiglas with the following dimensions: 40 mm length, 15 mm width and 3 mm height. It was horizontally placed under a microscope (Motic, China) equipped with an online digital camera. The images of the granule as well as produced biogas bubbles were regularly acquired at a fixed time interval.

2.3. Experiments in a stirred tank reactor

To study the effect of mean hydrodynamic shear rate, anaerobic reactions were performed in a CSTR system (Fig. 1). A double-jacketed stirred tank reactor (410 mL volume) was made of stainless steel with interior diameter 80 mm and height 80 mm. Sludge granules (37 gSS/L) were fed continuously with the same glucose solution (3000 mg COD/L) from the bottom of reactor by a Mariotte's bottle. The HRT was controlled at 5 h and the temperature was maintained at 35 °C with a thermostat. The estimated organic loading rate is about 14.4 kg COD/(m^3 d). It was stirred by a helical ribbon with appropriate dimensions (10 mm blade width, 70 mm pitch, 70 mm diameter) connected to a motor (Heidolph, Germany) whose rotational speed was at 12, 18, 24, 36, 60 rpm respectively. The biogas was collected by the displacement of water in an inversed graduated cylinder and analyzed by gas chromatography (Varian, USA). Before the continuous experiments, a batch experiment at 30 rpm was carried out to observe the evolution of biogas production. The continuous experiments at each stirring speed were maintained about two or three weeks until steady biogas production rate and methane content that were verified