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Super-high-rate performance and its mechanisms of a spiral symmetry stream anaerobic bioreactor

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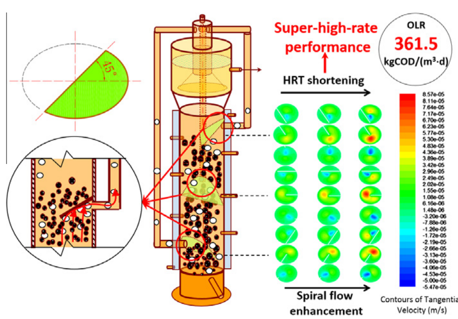
HIGHLIGHTS

- Three elliptic plates and gas collection pipes were set in a novel anaerobic reactor.
- The highest organic loading rate of the reactor was 361.5 kg COD/(m^3 d).
- The volumetric methane production and volumetric removal rate were improved.
- The gas entrapment role of the plates and pipes were beneficial to sludge keeping.
- The rich channels of granules provided a favorable environment for mass transfer.

GRAPHICAL ABSTRACT



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ABSTRACT

An anaerobic process, termed the spiral symmetry stream anaerobic bioreactor (SSSAB), had been developed by setting inner components of elliptic plates and gas collection pipes. And our previous study had demonstrated that a SSSAB was more efficient and stable than a same-sized up-flow anaerobic sludge bed (UASB) reactor. This study investigated the optimum treatment efficiency and super-high-rate mechanisms for the SSSAB. The performance with super-high-rate organic loading rate (OLR), volumetric removal rate (VRR) and improved volumetric methane production (VMP) of 361.5 kg COD/(m^3 d), 268.3 kg COD/(m^3 d) and 73.0 m^3/(m^3 d), respectively, were revealed for a lab-scale SSSAB. The elliptic plates set in the SSSAB could form spiral flow which increased along with the shortening of hydraulic retention time (HRT). The super-high-rate mechanisms were analyzed in terms of biomass, transfer condition around granules and sludge activity. The sludge retention ability in the SSSAB was achieved by the gas entrapment role of elliptic plates and gas collection pipes. The transfer condition around the granular sludge was changed to adapt to the variation of OLR. The rich channels of granules provided a favorable environment for substrate in and product out. The difference of methane productions between the batch test and the reactor operation illustrated that high substrate concentration and especially dramatic mixing condition in the SSSAB were significantly responsible for the super-high efficiency of SSSAB.

1. Introduction

Anaerobic biological technology is of the essence in the concentrated organic wastewater treatment, primarily due to the low energy and space requirement, low excess sludge production and

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positive energy balance (via biogas generation) in comparison to the conventional aerobic treatment process [1]. As the key environment for growth and metabolism of the anaerobic microorganism, the anaerobic bio-reactor's (AB) technology and efficiency breakthrough were always led by the innovation of the inner components (INCs). In 1970s, Lettinga et al. [2] developed the up-flow anaerobic sludge blanket (UASB) reactor, in which the sludge retention time (SRT) and the hydraulic retention time (HRT) were successfully separated, by inventing an INC of three-phase separator. Meanwhile the organic loading rate (OLR) of the plant-scale UASB reactors were increased to 4–8 kg COD/(m^3 d) due to the sludge granulation [3]. Subsequently the expanded granular sludge bed (EGSB) reactor [4] and the internal circulation (IC) reactor [5] were developed by means of adding INCs of the external circulation pipe and the internal circulation system (including two-stage three-phase separators, rising pipe etc.), respectively. And the OLR of those two reactors reached 20–40 kg COD/(m^3 d) in the plant-scale [1,6]. Since then researchers have shown an increased interest in the invention of differently configured INCs in the anaerobic reactor. For instance, van Lier et al. [7], Chen et al. [8], Ji et al. [9] all reported high-rate or even super high-rate [OLR $\geqslant$ 100 kg COD/(m^3 d)] anaerobic reactors equipped with different novel INCs. And recently, our group developed a spiral symmetry stream anaerobic bioreactor (SSSAB) by adding INCs of elliptic plates and gas collection pipes [10].

Traditionally, the application of an innovative anaerobic reactor regularly requires the process from lab-scale to pilot-scale then to plant-scale [11,12]. Though the volumetric removal rates (VRR) of ABs in the pilot- or plant-scale were experientially lower than that in the lab-scale due to the scale-up effect [11,13,14], the high VRR of an AB in the lab-scale resulted in the relatively high VRR of a corresponding AB in the larger scale. For example, the lab-scale UASB generally performed a VRR of 10–20 kg COD/(m^3 d) [2], and it was documented that a pilot-scale UASB reactor treating pharmaceutical wastewater had a VRR of 2–5 kg COD/(m^3 d) [15]; while a spiral automatic circulation reactor had VRRs of 240 in the lab-scale [8] and 22–30 kg COD/(m^3 d) in the pilot-scale treating pharmaceutical wastewater [16]. Thus, the treatment efficiency of an AB in the lab-scale could, in a way, reflect its treatment efficiency of that in the pilot- or plant scale.

Our previous study has demonstrated that the treatment efficiency and stability of a SSSAB were both more preferable than a same sized UASB reactor under room temperature [17]. However, the parameters about optimum treatment efficiency of the SSSAB are still limited. In this paper, a preliminary analysis of the effect of INCs on the reactor flow field was carried out; the super-high-rate operation of a SSSAB was conducted; the mechanism for SSSAB's efficient performance was studied in terms of biomass, transfer condition around granules and sludge activity.

2. Material and methods

2.1. Experimental set-up

The schematic diagram and photo of a SSSAB [10] were shown in Fig. 1(a) and (b). The SSSAB composed of several stainless steel hollow cylinders by flange connections. The effective volume and reaction volume of the SSSAB were 18.7 and 14.0 L, respectively. The SSSAB had total and sludge bed heights of 1225 and 850 mm. In the reaction zone of SSSAB three elliptic plates (Fig. 1(6)) were 120° spirally and symmetrically set. Then the sludge bed was divided into three chambers by the elliptic plates (Fig. 1(6)). Each chamber was provided with a gas collection pipe (Fig. 1(7)) with diameter of 25 mm to achieve respective biogas collection. The reaction zone were provided with an insulation layer (Fig. 1(8)), in which the circulating hot water was heated by a digital water bath (HH-4, Changzhou Zhiborui Instrument Manufacturing Co., Ltd.), in order to keep the temperature as 35 ± 1 °C in the reaction zone.

2.2. Inoculation and synthetic wastewater

The seed sludge was inoculated with methanogenic granular sludge from an EGSB reactor used for treating wastewater in a papermaking plant. The mean diameter of the seed sludge was 1.606 mm, and its density was 1.052 g cm^{-3} [18]. Moreover, the inoculation amount of the seed sludge was about 9.0 L, with a VSS/SS of 0.72.

The methanol and sodium acetate (with COD ratio 1:1) synthetic wastewater was adopted in the super-high-rate operation of SSSAB. The addition of NH_4Cl and KH_2PO_4 followed the C:N:P ratio of 300:5:1. The wastewater contained trace element solution I, II and nutrition solution of 1 mL L^{-1}, according to Tang et al. [19]. Because the alkalinity generation and consequently pH rising would happen along with the degradation of methanol and sodium acetate, the pH of the influent was adjusted to 6.6–6.8 to prevent alkali inhibition.

2.3. Super-high-rate operation strategy

The super-high-rate operation experiment was carried out after the complete start-up period (ended with influent COD of 10,000 mg/L and HRT of 12 h) of the SSSAB. The super-high-rate operation strategy of the SSSAB was given in Table 1. The whole experiment was divided into two phases, the substrate concentration increasing (phase I) and the HRT shortening (phase II). In the former phase, on the premise of HRT of 12 h, the initial COD concentration of the influent was 10,000 mg/L, and the influent COD concentration would increase by 2000 mg/L if the COD removal rate of the reactor was stable. The objective of this phase was to explore the highest and most suitable COD concentration to carry on the HRT shortening trial. In the latter phase, on the premise of constant COD concentration, the HRT was shortened step by step when the COD removal rate of the reactor was stable, in order to figure out the highest OLR and VRR of the SSSAB.

2.4. Methanogenic activity assays

All methanogenic activity assays were performed in 118 mL serum bottles with triplicate vials. Each bottle received mixed liquid containing about 1.2 g VSS of sludge from the SSSAB. The bottles were added with 1 mL L^{-1} nutrition and trace solutions mentioned above. The headspaces were flushed with nitrogen gas and the bottles were sealed with butyl rubber stoppers. After a 2-day preincubation period (in a rotary shaker with 105 rpm at 36 °C), the headspace of the vials was again flushed and 30 mL 2500 mg/L neutralized sodium acetate solution was added. In each bottle 0.5 mL of 10 g/L Na_2S solution was added to adjust the redox potential. The vials were incubated on rotary shaker with 105 rpm at 36 °C. The methane produced was collected by 50 mL Smith fermentation tube filled with 2 mol/L NaOH – saturated NaCl solution. The VSS of the sludge in each bottle was measured at the end of the trial. Assays without sludge were also carried out as control. The specific methanogenic activity (SMA) were calculated from the steepest slope of cumulative methane production curves (expressed in mL CH_4 per gram VSS per day).

2.5. Analytical methods

COD, SS and VSS were carried out following the Standard Methods [20]. pH was tested by PXSJ-216 ion meter combined with