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Dispersion characteristics of a spiral symmetry stream anaerobic bio-reactor

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ABSTRACT

The dispersion characteristics of an anaerobic reactor affect its flow patterns and consequently impact its removal efficiency η (assumed). The dispersion characteristics of a spiral symmetry stream anaerobic bio-reactor (SSSAB) were investigated under overall and local dispersion conditions, which were well described by the axial dispersion model and increasing-sized CSTRs model, respectively. The flow patterns of the SSSAB under super-high (hydraulic loading rate $L = 18.45\,\mathrm{L\,L^{-1}\,d^{-1}}$, biogas production rate $G = 80.24\,\mathrm{L\,L^{-1}\,d^{-1}}$) and high loadings ($L = 9.23\,\mathrm{L\,L^{-1}\,d^{-1}}$, $G = 40.12\,\mathrm{L\,L^{-1}\,d^{-1}}$) tended to the completely mixed flow, while under middle ($L = 4.61\,\mathrm{L\,L^{-1}\,d^{-1}}$, $G = 20.06\,\mathrm{L\,L^{-1}\,d^{-1}}$) and low loadings ($L = 2.31\,\mathrm{L\,L^{-1}\,d^{-1}}$, $G = 10.03\,\mathrm{L\,L^{-1}\,d^{-1}}$) tended to the plug-flow. The axial dispersion decreases along the height of the SSSAB. The fluid in the reactor mixed completely after the actual completely mixed time θ_{acm}, which decreases from 1.54 to 0.44 with the loading rate increases. The maximum and minimum values of the mean increasing rate v_{m} are 14.00 and 0.72 at super-high and loading rate, respectively. And η positively correlates to the number of tanks N and negatively to v_{m}. Reducing v_{m} and enlarging N are the favorable method to further improve the treatment efficiency for the reactor operated under low or medium loading and high or super-high loading conditions, respectively.

1. Introduction

Anaerobic bioreactor (AB) is a popular option for the biological treatment of high-strength wastewater with a soluble organic fraction [1]. Among them the upflow anaerobic sludge bed reactor (UASBR) [2] was one of the most widespread ABs applied in the world. And the UASBR separated the sludge retention time (SRT) and hydraulic retention time (HRT) successfully via the three phase separator [3]. Later, in order to improve the hydraulics in ABs, the third-generation ABs were developed, including the internal circulation reactor (ICR) [4] and expanded granular sludge bed reactor (EGSBR) [5]. Due to the hydraulic improvement and consequently the phase-phase mass transfer enhancement, the treatment efficiencies of the ICR and EGSBR were further optimized.

Recently, a spiral symmetry stream anaerobic bioreactor (SSSAB) [6] was invented by our project group for improving the hydraulics as well. Compared to the conventional UASBR, the SSSAB has three elliptic plates spirally and symmetrically set in sludge bed for optimizing the flow pattern in the reaction zone. It also collects the gas in the area underneath three elliptic plates [Fig. 1(c)] to reduce the effect of bubble wake entrainment and medium gaseous products inhibition. And our pre-study showed that a SSSAB operated more efficient and stable than a same sized UASBR [7]: the mean value of COD removal rates of the SSSAB was 1.2 times as high as that of the UASBR; the mean coefficient variation value (in terms of removal efficiency, adsorption property, settling ability, flocculability) of the SSSAB was 0.67 times as that of the UASBR. Apparently the structure optimization (elliptic plate installment and respective gas collection) makes a contribution to the performance enhancement for the SSSAB by improving its hydraulics. And a key feature in hydraulics of a reactor is its dispersion characteristics [8], which affect the reactor flow patterns, substrate transfer between phases, and consequently impact its removal efficiency. Therefore, the dispersion characteristics of SSSAB are necessary to be investigated.

The residence time distribution (RTD) technique was chosen to study the dispersion characteristics of SSSAB because it's

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Nomenclature

C_0	Initial tracer concentration (mg L^{-1})
$C(t)$	Tracer concentration at time t (mg L^{-1})
$C(\theta)$	Tracer concentration at normalized time θ (mg L^{-1})
D/uL	Vessel dispersion number
$E(t)$	Exit-age distribution function
$E(\theta)$	Normalized concentration
G	Biogas production rate (L L^{-1} d^{-1})
L	Hydraulic loading rate (L L^{-1} d^{-1})
N	Number of tanks
Q	Influent flow rate (L min^{-1})
R^2	Fitting coefficient
r	Volume fraction coefficient
t	Time (min)
$\bar{t}$	Mean residence time (min)
v_i	Dispersion decreasing rate between CSTR$_i$ and CSTR$_{i+1}$
v_m	Mean dispersion decreasing rate
V_{bd}	Biological dead space
V_{hd}	Hydraulic dead space
V_i	Volume of i-th CSTR (L)
V_{td}	Total dead space
V_{tot}	Total volume of the reactor (L)
z	Dimensionless length

Greek letters

η	Removal efficiency
θ	Normalized time
θ_{acm}	Actual completely mixed time
θ_{peak}	Normalized time of the concentration peak
ρ_e	Substrate concentration in the effluent (mg L^{-1})
ρ_{i_e}	Substrate concentration in the effluent for i-th CSTR (mg L^{-1})
ρ_{i_in}	Substrate concentration in the influent for i-th CSTR (mg L^{-1})
ρ_{in}	Substrate concentration in the influent (mg L^{-1})
$\sigma 2\ t$	Variance of the residence time distribution (RTD) curve (mg L^{-1})
$\sigma 2\ \theta$	Dimensionless variance of the RTD curve
τ	Hydraulic retention time(HRT) (min)
τ_i	HRT of i-th CSTR (min)
τ_{tot}	HRT throughout the whole anaerobic reactor (d)
χ^2	Squared difference

Subscripts

i	i-th element of function
j	j-th element of function
k	k-th element of function

easy to carry out and comprehensive to evaluate the reactor hydraulics with the model establishment. In the past researches, the axial dispersion model and tank-in-series model were often employed to describe the flow patterns of ABs [9,10], as well as the CSTR(continuous stirred tank reactor) models with some short-circuiting, bypass flows and dead zones [11–14]. Based on the conventional equal-sized CSTRs model (ESC model or tank-in-series model), an increasing-sized CSTRs (ISC) model was put forward for featuring the dispersion non-uniformity in ABs [15]. And it was verified that compared to the ESC model, the ISC model can characterize the dispersion characteristics of the UASBR better.

Considering that, as the improvement of the UASBR, the SSSAB's dispersion characteristics may be non-uniform as well. Therefore, the overall dispersion study were firstly carried out, and it was analyzed by the typical axial dispersion model under close boundary condition. And the ISC model was chosen to illustrate the local dispersion feature because of the inaccuracy of axial dispersion model under open boundary condition. Moreover, we developed the relationship among the removal efficiency, the number of tanks and the mean dispersion decreasing rate. And suggestions were given to further improve the treatment efficiency of a given reactor under different loading conditions.

2. Materials and methods

2.1. Experimental set-up

The schematic diagram and photo of a SSSAB were shown in Fig. 1. The SSSAB was made of stainless steel and its configuration parameters were: bed (column) diameter 0.150 m, bed height 0.900 m, separation unit diameter 0.150 m and height 0.325 m, respectively. The total height of reactor was 1.225 m. The upper and lower diameters of the three-phase separator [Fig. 1(9)] were 0.050 m and 0.120 m, respectively. The available volume and bed volume of SSSAB were 18.65 L and 15.00 L, respectively. For the SSSAB three elliptic plates [Fig. 1(6), $\alpha = 40–60$] were 120 spirally symmetrically set in the reaction zone. The angle between the elliptic plate and the wall of the reactor was about 50. Then the sludge bed was divided into three chambers. Each chamber was provided with a gas collection pipe [Fig. 1(7)] with diameter of 0.025 m to achieve respective biogas collection. Wastewater was pumped into the distribution zone of the reactor by a peristaltic pump[Fig. 1(2)], then was treated in the reaction zone of the reactor, finally went off the reactor in the separation zone through the three-phase separator [Fig. 1(9)].

The seed sludge was obtained from an EGSB reactor used for treating wastewater in a papermaking plant [16]. The surface mean diameter (SMD) of the seed sludge was 1.606 mm, and its density was 1.052 g cm^{-3}. Moreover, the inocula amount of the seed sludge was 2.5 L (excluding void between granules). The VSS (volatile suspended solids)/SS (suspended solids) of the inocula was 0.72.

2.2. Experimental methods

In order to simulate biogas production rate (BPR) accurately, the saturated sodium bicarbonate and sulfuric acid solution (0.5%, w/w) was employed as influent, resulting in the production of CO_2 by the chemical reaction. However, the maximum CO_2 production rate was about 40 L L^{-1} d^{-1} by this method. And the simulated BPR was 80.24 L L^{-1} d^{-1} starting from an initial value of 10.03 L L^{-1} d^{-1}. So extra air was pumped into the SSSAB in different directions and heights as simulated BPR auxiliary through an air pump. The gas flow control valves were used for ensuring the total simulated BPR ranging from 10.03 and 80.24 L L^{-1} d^{-1}. The simulated hydraulic loading rate (HLR) was in the range of 2.31–18.45 L L^{-1} d^{-1} while hydraulic retention time (HRT) ranged from 624 to 78 min.

We employed the stimulus-response technique that a pulse injection of tracer was performed at time of 0 at influent pipe by an injector in less than 2 s. The sodium fluoride (NaF) was used in this study because it was not significantly adsorbed and non-degradable by biomass [10]. A solution containing 80 mg NaF (36 mg F) was injected during each tracer run. And the tracer concentration sampled from the sampling ports (effluent in overall dispersion study and bottom, middle, top and effluent in local dispersion study) was filtered then measured by a fluoride ion-selective electrode (PF-1-01, Shanghai INESA Scientific Instrument Co., Ltd.). According to the tracer concentration off the reactor the exit time distribution for a pulse input could be obtained to represent the RTD of the fluid, $E(t)$.