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Modelling and predicting transport and concentration distribution of sludge in a high performance anaerobic bioreactor

Ruobin Dai[a,b], Xiaoguang Chen[a,b,*], Puyue Ma[a], Xiaoxiao Chu[a], Xinyi Xiang[a], Ying Luo[a], Shengsheng Ni[a], Gang Li[a]

[a] College of Environmental Science and Engineering, Donghua University, Shanghai 201620, China
[b] State Environmental Protection Engineering Center for Pollution Treatment and Control in Textile Industry, Shanghai 201620, China

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ABSTRACT

The transport and concentration distribution of sludge in a high performance anaerobic bioreactor, termed spiral symmetry stream anaerobic bioreactor (SSSAB), was directly related to its effective retention of the biomass, as well as its stable operation under high loading rate. Therefore, the transport and concentration distribution of sludge in a lab-scale SSSAB were modelled and investigated in comparison with a same-sized upflow anaerobic sludge blanket reactor (UASBR), and two larger scale SSSABs were used for validating and expanding the application field of the model. The results showed that the model established can effectively describe the sludge transport and concentration distribution in the SSSAB. The SSSAB performed relatively low sludge transport factor compared with the UASBR, proving the favorable sludge retention ability of the SSSAB. The sludge transport factor remained constant with the scale-up of the SSSAB. The model could predict the sludge concentration distribution of a 130 L SSSAB treating traditional Chinese pharmaceutical wastewater. Also, the model can be applied to the SSSAB treating other types of wastewater with biogas production fractions in zone 1 and 2 (f_1 and f_2) at the ranges of 0.19–0.41 and 0.18–0.41, respectively.

1. Introduction

The construction of a sustainable society requires reduction of dependency on fossil fuels and lowering of the amount of pollution generated [1,2]. Anaerobic biological wastewater treatment has been holding much promise as a green technology for the removal of organic contaminants and exploitation of energy (e.g. methane) [3], particularly since the emergence of high-rate anaerobic bioreactors (HRABs). During past decades, typical HRABs were successively developed for enhancing volumetric organic loading of reactors, consequently reducing the reactor volume required and even further improving the removal efficiency. These HRABs included upflow anaerobic sludge blanket reactor (UASBR) [4], expanded granular sludge bed (EGSB) anaerobic reactor [5], internal circulation (IC) anaerobic reactor [6], etc.

For the same purpose, a high performance anaerobic bioreactor with an organic loading rate (OLR) up to 361.5 kg COD/(m^3 d), termed spiral symmetry stream anaerobic bioreactor (SSSAB) [7] was invented recently. The mechanisms of high performance of the SSSAB have been studied in terms of hydraulic characteristics [8], physicochemical properties [9,10] and methanogenic activity [7] of the anaerobic granules etc. Nevertheless, the transport and concentration distribution of the sludge in the SSSAB was still not clear.

In our previous study demonstrating a 4 L SSSAB for a better treatment efficiency and stability than a same sized UASBR [10], sludge washout was noticed for the UASBR spiked by the abruptly increased influent COD concentration and biogas production. Also, severe sludge loss occurred for a UASBR as control (even not described in the literature because the UASBR collapsed too early) during super-high-rate operation of an 18.65 L SSSAB [7]. However, phenomenon of sludge washout was, by contrast, hardly observed for the SSSAB. It means that the SSSAB perhaps holds more advantageous sludge concentration distribution or transport

* Corresponding author at: Room 4161, 2999 Renmin North Road, Songjiang District, Shanghai, 201620, China.
E-mail address: cxg@dhu.edu.cn (X. Chen).

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Nomenclature

A_R	Bottom area of the reactor, m^2
A'_R	Bottom area of the reactor (A_R) minus the shaded area of one semi-elliptical plate on the bottom area, m^2
$C_{m,i}$	Sludge concentration (SS) in zone i, g/L
$C_{m,i+1}$	Sludge concentration (SS) in zone i + 1, g/L
f_1	Fraction of biogas produced in zone 1, dimensionless
f_2	Fraction of biogas produced in zone 2, dimensionless
$F_{w,i[i+1]}$	Upward mixed flow caused by biogas production from zone i to i + 1, m^3/s
$F_{[i+1]i}$	Downward mixed flow caused by back-mixing stream from zone i + 1 to i, m^3/s
h_i	Height at the top of zone i, m
h_t	Height at the liquid level in the reactor, m
$k_{m,i[i+1]}$	Transport constants of gas wakes from zone i to i + 1, dimensionless
$k_{m,[i+1]i}$	Sludge transport constant of back-mixing stream from zone i + 1 to i, dimensionless
$k_{t,i[i+1]}$	Transport factor of sludge from zone i to i + 1, dimensionless
$k_{t,[i+1]i}$	Transport factor of sludge from zone i + 1 to i, dimensionless
$k_{w,i}$	Volume of liquid transported upward per volume of gas produced in zone i, dimensionless
R^2	Fitting correlation coefficients, dimensionless
$v'_{g,i}$	Superficial upflow gas velocity in zone i, m/s
$v_{s,i+1}$	Free settling velocity of granular sludge, m/s
$v'_{s,i+1}$	Hindered settling velocity of granular sludge, m/s
v_L	Superficial upflow fluid velocity, m/s
$\phi_{g,i}$	Total biogas produced by sludge in zone i, m^3/s
$\phi'_{g,i}$	Gas production excluding gas collected in zone i, m^3/s
$\phi''_{g,i}$	Gas production collected in zone i, m^3/s
$\phi''_{g,i,t}$	Biogas of zone i measured located on the liquid level in the reactor, m^3/s
$\phi_{m,i[i+1]}$	Upward sludge streams from zone i to i + 1, m^3/s
$\phi_{m,[i+1]i}$	Downward sludge streams zone i + 1 to i, m^3/s

condition than the UASBR, which requires further demonstrations. Additionally, the sludge concentration distribution of the SSSAB is directly related to its retention of the anaerobic biomass, i.e. the high concentration in upper part of sludge bed or in sludge blanket may cause sludge washout. The continuous loss of biomass will result in the deterioration of effluent quality, or even the breakdown of the bioreactor. Thus, it is critical to model and then predict the transport and concentration distribution of the sludge in the SSSAB, which could warn operator in advance to prevent sludge from washout and keep the bioreactor stable.

Based on the mass balance, Buijs et al. [11] and Chen et al. [12] has modelled the sludge dynamic behavior of the UASBR and the spiral anaerobic (SPAC) reactor, respectively, and provided models for the prediction of sludge concentration distribution in the reactor. However, their predictions were proved to be useful only towards one type of wastewater for each reactor, i.e. the wastewater containing partly neutralized fatty acids for the UASBR and the sucrose synthetic wastewater for the SPAC. The availability of those models for the prediction with respect to other types of wastewater seem to be uncertain. Furthermore, in their modelling process they assumed that the production of biogas was uniform along the height. But the real wastewater feeding anaerobic reactors often results in non-uniform vertical biogas production, e.g. the volatile fatty acids (VFA) dominated wastewater induces high biogas production in the lower part of the sludge bed, while the recalcitrant wastewater in the upper part of the sludge bed.

In this work, we developed a mathematical model based on Buijs et al. [11] and Chen et al. [12] according to the structure of the SSSAB. The model based study on the transport and concentration distribution of sludge in a 7.45 L SSSAB was carried out, taking a same sized UASBR as comparison. Simultaneously, an 18.65 L SSSAB was operated to test whether the sludge transport factors would change with the scale-up. Since the traditional Chinese pharmaceutical wastewater has the feature that its composition and biodegradability vary with the production condition, this kind of wastewater feeding a 130 L SSSAB was employed to validate the predictability of the developed model under different vertical biogas production distributions.

2. Model establishment

For a SSSAB [Fig. 1(a)] operated steadily to treat a certain wastewater with constant water quality, a physical model for the sludge transport and concentration distribution in the SSSAB could be established based on the mass balance. In the physical model [Fig. 1(c)], the SSSAB was divided into three parts including settler, sludge blanket and sludge bed. Biogas collections caused by the plates and gas collection pipes [Fig. 1(b)] were also considered in the physical model. Furthermore, following situations regarding sludge can often be recognized:

(i) Since the true yield of anaerobic granular sludge was low [13] and washout of sludge rarely occurred due to the high efficiency of three-phase separator [5], the total amount of sludge was assumed constant in each anaerobic bioreactor during short stationary periods (<15 d).

(ii) As the installation of semi-elliptical plates, the sludge bed was further separated into three parts [Fig. 1(c)]. Three parts of sludge bed and sludge blanket were defined as zone 1–4 from bottom to top of the reactor, respectively. Under a given operational condition, the sludge concentration in the bed was constant in time and did not vary with the axial and radial distance in each parts of the bed (i.e., $C_{m,i}$ = constant, i = 1–4), because the liquor in each parts can be regarded as completely mixed [8]. It also indicated that the biogas production from sludge was horizontally uniform.

(iii) According to the definition of hydraulic radius considering the wall effect in the column reactor [14], since the wetted surface area of anaerobic granular sludge in the reactor was significantly larger than that of reactor wall, wall effects in the anaerobic reactor was thus ignored.

2.1. Sludge transport and concentration distribution in SSSAB

Two distinct transport stream (upward and downward sludge streams) of sludge existed in the vertical direction of the bioreactor. Under the condition that the total amount of sludge was assumed constant, equal relation can be found between the upward ($\phi_{m,i[i+1]}$, m^3/s) and downward sludge streams ($\phi_{m,[i+1]i}$, m^3/s):

$$\phi_{m,i[i+1]} = \phi_{m,[i+1]i} \quad i = 1, 2, 3 \tag{1}$$

The upward sludge stream ($\phi_{m,i[i+1]}$) was mainly driven by the wakes of the gas bubbles, which entrained sludge from zone i to zone i + 1 (i = 1, 2, 3). The influence of upflow liquid on upward sludge stream was neglected because the superficial upflow fluid velocity (v_L, m/s) in the bioreactor was always small compared with