Influence of agitation rate on the performance of a stirred anaerobic sequencing batch reactor containing immobilized biomass

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Abstract The present work reports on the influence of the mechanical agitation rates on the performance of a stirred anaerobic sequencing batch reactor containing immobilized biomass on polyurethane foam, as inert support, treating synthetic domestic wastewater. The reactor was operated at 30°C and an 8-hour cycle was used to treat approximately 0.5 L of the synthetic substrate with a COD concentration of nearly 500 mg/L. The studied agitation rates ranged from no agitation to 750 rpm. The system attained non-filtered substrate removal efficiency greater than 83% when agitation was employed. A very short start-up period and good solid retention could be observed. The use of agitation increased the efficiency of the reactor and enabled reduction of the total cycle time. An empirical equation and a first-order kinetic model are proposed to analyze the influence of agitation rates on the reactor's performance.

Keywords Anaerobic process; immobilized biomass; low strength wastewater; polyurethane foam; stirred sequencing batch reactor; wastewater treatment

Introduction

The anaerobic sequential batch reactor (ASBR) is an alternative to the anaerobic wastewater treatment. Greater biomass retention, better effluent quality control, elimination of the primary and secondary sedimentation steps, relatively high efficiency and simple operation are its principal advantages over the continuous process.

A typical cycle in an ASBR is composed of four steps: feed, reaction, settling and liquid withdrawal (Dague *et al.*, 1992). The first step, i.e. feeding of the reactor, which contains the anaerobic biomass, defines the operation system as batch or fed-batch, according to the duration of this step in relation to the overall cycle time. During the reaction step, organic matter is consumed with production of biogas. Reactor performance is closely related to the kind of biomass–substrate contact, which is a function of the degree of agitation of the reaction medium. Upon termination of the reaction, the settling step takes place, leading to the sediment of the biomass. This step is related to the settleability characteristics of the sludge. The next step is the liquid withdrawal, where the flow rate should be defined in a way to favor retention of the settled biomass. Subsequently, the cycle is reinitiated.

The method and intensity of agitation applied to the reaction medium is expected to have significant influence on the process performance, in virtue of the relationship with the mass transfer from the liquid medium to the granulated biomass surface in the reaction step, as well as on the development of the favorable settleability characteristics of the biomass in the settling step.

In anaerobic sequencing batch reactors, agitation is performed mainly by recirculating the produced biogas. In systems containing aggregated biomass, agitation by biogas recirculation may reduce the solid retention in the settle step due to the rupture of granules when agitation is relatively intense, or may enhance the gas–solid separation efficiency by improving the sludge settleability when agitation takes place intermittently (Angenent and Dague, 1995).

When low strength wastewaters are treated, the biogas production may be insufficient to provide enough mixing in the reactor and an alternative method of agitation might be necessary, like liquid recycling or mechanical agitation (Brito *et al.*, 1997; Pol *et al.*, 1998). Some indicative results about agitation strategies have been presented in the literature (Droste and Massé, 1995; Sung and Dague, 1995; Hirl and Irvine, 1996; Zhang *et al.*, 1996). However, investigations related to the agitation intensity by gas recirculation or by the use of mechanical agitation have not been encountered so far.

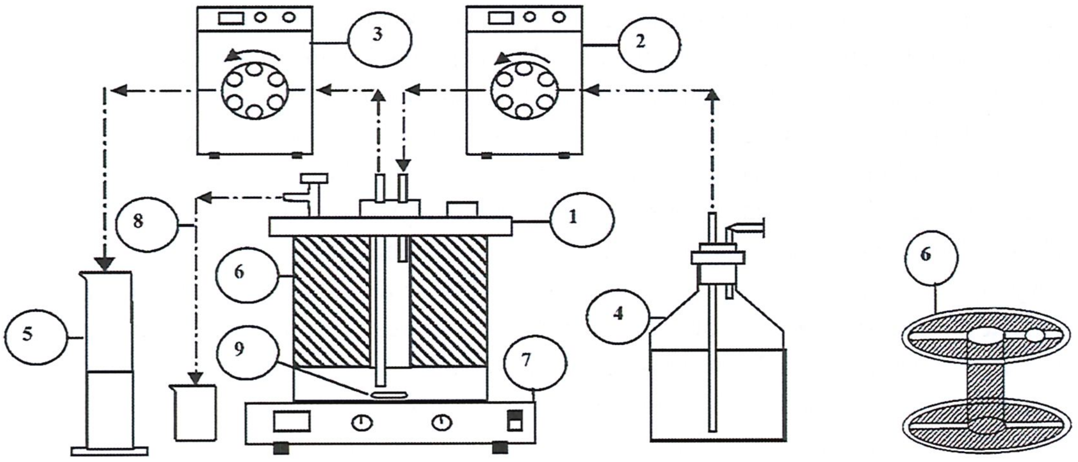
On implementing agitation to improve biomass–substrate contact, optimization of the process will be limited by the duration of the settle step, as this step may represent a substantial part of the total operation cycle time. Immobilized biomass in inert supports has been used in order to minimize the solid washout observed in reactors containing granulated biomass, permitting the elimination of the settle step and decreasing the total cycle time. In addition, the immobilization of biomass in inert supports eliminates the uncertainty inherent in the sludge granulation (Ratusznei *et al.*, 2000).

The main purpose of the present work is to study the influence of the mechanical agitation rates on the performance of an anaerobic sequencing batch reactor containing immobilized biomass on polyurethane foam.

Materials and methods

The bench-scale anaerobic sequencing batch reactor shown in Figure 1 consists of a cylindrical flask with a diameter of 15 cm (total capacity, 2.5 L) containing 1.0 L of aqueous medium. This configuration was first proposed by Ratusznei *et al.* (2000). Cubic particles of polyurethane foam (5-mm side; 23-kg/m^3 apparent density) in a basket were used as support material for biomass immobilization. Agitation was supplied by means of a stirring bar at the bottom of the reactor.

The sludge inoculum was taken from a pilot-plant continuous anaerobic baffled reactor treating domestic sewage. The total suspended solids concentration (TSS) was around 56,000 mg/L and the volatile suspended solids concentration (VSS) was 38,000 mg/L. One litre of the inoculum was thoroughly mixed with 30 g of cubic polyurethane particles, resulting in total solids concentration (TS) of 1,694 mg/g-foam, volatile solids concentra-



(a) (b)

Figure 1 (a) Scheme of the reactor (1-reactor; 2-feed pump; 3-discharge pump; 4-wastewater reservoir; 5-effluent; 6-basket containing the immobilized biomass; 7-magnetic stirrer; 8-gas outlet; 9-stirring bar); (b) basket in detail tion (VS) of 1,049 mg/g-foam, total suspended solids concentration (TSS) of 1,583 mg/g-foam and volatile suspended solids concentration (VSS) of 980 mg/g-foam. Hence, the volatile suspended solids content in the bioreactor was 29.4 g.

The synthetic wastewater with COD concentration of approximately 500 mg/L was prepared with sucrose (35 mg/L), starch (114 mg/L), cellulose (34 mg/L), meat extract (208 mg/L), soy oil (51 mg/L), NaCl (250 mg/L), $MgCl_2.6H_2O$ (7 mg/L), $CaCl_2.2H_2O$ (4.5 mg/L), $NaHCO_3$ (200 mg/L), and commercial detergent (3 drops/L). The medium was sterilized (121°C, 15 min) in order to maintain its characteristics during the experimental time.

The reactor was operated at 30 ± 1°C in an 8-hour cycle sequential batch. A volume of 0.5 L of fresh synthetic wastewater was fed for 3 min and, at the end of the cycle, 0.5 L of the treated medium was also discharged in 3 min. The organic loading was 289 ± 29 mgCOD/L.d and the specific organic loading was 24.6 ± 2.5 mgCOD/gvss.d, estimated using the affluent volume, the total cycle time, the total reactor volume and the volatile suspended solids content in the bioreactor.

The system was operated at agitation rates of 500 rpm for 36 days (108 consecutive cycles), no agitation for 111 days (333 consecutive cycles), 100 rpm for 80 days (240 consecutive cycles), 200 rpm for 41 days (123 consecutive cycles), 750 rpm for 40 days (120 consecutive cycles), 350 rpm for 37 days (111 consecutive cycles) and 50 rpm for 59 days (177 consecutive cycles). This sequence was chosen in order to assure that the modifications in the reactor's performance were due to the different agitation rates implemented and not to the biomass acclimatization.

Substrate concentration measures as COD, total volatile acids concentration (TVA), bicarbonate alkalinity concentration (BA), volume discharged and pH were monitored in both the influent and effluent in different cycles for all conditions according to *Standard Methods for the Examination of Water and Wastewater* (1995) procedures.

The overall substrate removal efficiencies, based on non-filtered (ε_T) and filtered (ε_S) samples and the substrate removal efficiency in the reactor (ε_i) were calculated by Equations (1), (2) and (3) respectively, where C_I is non-filtered concentration of substrate in the influent, C_{ET} is the non-filtered concentration of substrate in the effluent, C_{ES} is the filtered concentration of substrate in the effluent, C_S is the filtered concentration of substrate in the reactor, C_{SO} is the initial value of C_S.

$$\varepsilon_T = \frac{C_I - C_{ET}}{C_I} \tag{1}$$

$$\varepsilon_S = \frac{C_I - C_{ES}}{C_I} \tag{2}$$

$$\varepsilon_i = \frac{C_{So} - C_S}{C_{So}} \tag{3}$$

When the filtered substrate, bicarbonate alkalinity and total volatile acids effluent concentrations presented no significant variation from one cycle to another, the filtered substrate profile along the cycle was obtained in order to evaluate the influence of agitation rate on the performance of the reactor under the described experimental conditions. The dynamic conversion profile was obtained at the condition of stable reactor in order to verify how organic consumption takes place and, hence, optimize operation of the system, i.e., to estimate the cycle time effectively necessary for removal of the organic matter.

To obtain the concentration-time profile for the condition without agitation, the medium must be homogenized just before the sample withdrawal in order to assure the measurement of the actual average concentration of the substrate in the reactor. For this reason, the following procedure was adopted. In a given cycle, at a certain time, t_1, the medium was agitated (500 rpm for 3 min) and then the sample withdrawal was performed leading to the first point of the profile. After the completion of the above cycle, three consecutive undisturbed cycles were run in order to eliminate the disturbance produced by the cited agitation. Then, during the next cycle, at time $t_2 > t_1$, the second sample withdrawal was carried out as described above leading to the second point of the profile. The above operation was repeated to obtain the entire profile in duplicate.

When the experiment was carried out with agitation, the entire profile was obtained in a single cycle. In this case, however, after the addition of fresh wastewater to the reactor, a suitable time interval must lapse before the first sample withdrawal in order to assure the homogeneity medium in the reactor. The above time interval depends on the chose of the value of agitation rate for the test. According to the hydrodynamic study reported by Ratusznei *et al.* (2000) the following time intervals were adopted: 15 min for 50 rpm, 13 min for 100 rpm, 7 min for 200 rpm, 5 min for 350 rpm and 3 min for 500 and 750 rpm. These profiles were obtained in triplicate.

The analysis of the influence of agitation on the reactor's response was performed by linear fitting both the empirical correlation represented by Equation (4) and the first-order kinetic model represented by Equation (5) to the temporal profiles of COD removal efficiencies. The physical meaning of parameter a_1 is the maximum conversion obtained in the reactor, and that of a_2 is the time necessary for the conversion to attain 50% of its maximum value. The fitting of a first-order kinetic model, represented by Equation (5), enabled estimation of the parameter k_1, which represents the apparent kinetic coefficient, as it embodies the intrinsic kinetic as well as internal and external mass transfer resistances.

$$\varepsilon_i = \frac{a_1 t}{a_2 + t} \tag{4}$$

$$R_s = \mu_S C_X = -\frac{dC_S}{dt} = k_1 \left(C_S - C_{SR}\right) \tag{5}$$

It is worth pointing out the consideration of a residual concentration value of filtered substrate (C_{SR}), where the value of the substrate uptake rate (Rs) and the specific substrate uptake rate (μs) were zero, and of a biomass concentration (Cx) constant throughout the assays. The parameter of this model was estimated through the differential method by estimating the experimental reaction rate by the Le Duy and Zajic procedure (1973).

Results and discussion

The operating variables monitored during the tests and the corresponding standard deviations, obtained at several operating agitation rates (N), are presented in Tables 1 and 2. The specific organic removal (SOR) was calculated using the suspended volatile solids content in the bioreactor. The average conversion values show that a relatively high efficiency was attained at all agitation rates. Moreover, the removal efficiency values based on non-filtered (ε_T) and filtered (ε_S) samples are very much alike, indicating that no significant loss of solids occurred during discharge, i.e., there was a high solids retention in the system; this fact was confirmed by the values of total suspended solids of both the influent and effluent. Stability was confirmed by the low volatile acid concentration values and by the generation of bicarbonate alkalinity concentration in the system.

The parameters a_1 and a_2 obtained from the fit of Equation (4) and the parameter k_1 obtained from the fit of Equation (5) are listed in Table 3 as a function of the investigated agitation rates. The parameters a_2 and k_1 were fitted to an empirical correlation, shown in

Equations (6) and (7). Figure 2 presents the variation profile of parameters a_2 and k_1 as a function of agitation rate, respectively, disregarding the condition with no agitation, due to the discrepant parameter values observed at this condition.

$$a_2 = 1.55 - 0.42 \log N \tag{6}$$

$$k_1 = -0.36 + 0.67 \log N \tag{7}$$

The agitation rate was found to affect sensitively the time necessary to achieve the maximum efficiency in a cycle. This influence might be credited to the improvement in the mass transfer between the fluid substrate and the immobilized anaerobic biomass. However, no significant improvement was observed in the substrate removal efficiency at the end of the cycle. The organic matter removal conversion profiles estimated by Equation (4) and the organic matter removal conversion rates estimated by the first-order model (Equation 5) during the batch are shown in Figures 3 to 6, indicating that a cycle of approximately 3 hours would be sufficient to obtain a reasonable removal efficiency. In this way,

Table 1 Monitored parameters in the reactor operated at different agitation rates

N (rpm)	C_I (mgCOD/L)	C_E (mgCOD/L)		ε (%)		SOR	V (mL)
		C_{ET}	C_{ES}	ε_T (%)	ε_S (%)	(mgCOD/gvss)	
0	476 ± 22	127 ± 18	107 ± 13	73 ± 4	78 ± 3	6.0	503 ± 26
50	481 ± 31	83 ± 19	65 ± 12	83 ± 4	86 ± 3	6.5	483 ± 26
100	465 ± 30	62 ± 13	57 ± 10	87 ± 3	88 ± 2	6.9	501 ± 28
200	477 ± 25	74 ± 15	65 ± 9	85 ± 3	86 ± 2	7.0	507 ± 29
350	493 ± 42	57 ± 8	52 ± 6	89 ± 2	90 ± 1	6.8	460 ± 28
500	485 ± 49	68 ± 10	37 ± 6	86 ± 2	92 ± 2	7.1	497 ± 25
750	472 ± 24	55 ± 6	52 ± 6	88 ± 1	89 1	6.9	487 ± 28

Table 2 Monitored parameters in the reactor operated at different agitation rates

N (rpm)	BA (mgCaCO$_3$/L)		TVA (mgHAc/L)		pH	
	Influent	Effluent	Influent	Effluent	Influent	Effluent
0	121 ± 15	192 ± 29	36 ± 14	50 ± 19	8.9 ± 0.5	6.9 ± 0.1
50	119 ± 16	278 ± 61	61 ± 4	48 ± 23	8.3 ± 0.8	6.9 ± 0.1
100	158 ± 12	214 ± 11	32 ± 9	20 ± 6	8.9 ± 0.5	7.0 ± 0.2
200	120 ± 10	217 ± 10	32 ± 9	20 ± 6	8.9 ± 0.4	7.0 ± 0.2
350	108 ± 40	285 ± 70	65 ± 14	28 ± 13	8.1 ± 0.7	7.0 ± 0.1
500	120 ± 2	211 ± 2	20 ± 2	10 ± 3	9.1 ± 0.2	6.7 ± 0.1
750	119 ± 16	270 ± 60	61 ± 4	50 ± 16	8.6 ± 0.8	6.9 ± 0.1

VSS Influent = 37 ± 21 mg/L; VSS Effluent = 29 ± 21 mg/L.

Table 3 Values of parameters a_1 and a_2 from empirical correlation (Equation 4) and k_1 and C_{SR} from the first-order model (Equation 5) and the respective determination coefficient r^2

N (rpm)	a_1	a_2 (h)	r^2 (Equation 3)	k_1 (h^{-1})	C_{SR} (mgCOD/L)	r^2 (Equation 4)
0	0.56	0.38	0.909	1.44	108	0.956
50	0.78	0.86	0.947	0.78	60	0.972
100	0.76	0.67	0.946	1.05	70	0.984
200	0.78	0.62	0.922	1.14	70	0.960
350	0.83	0.45	0.984	1.36	50	0.966
500	0.78	0.42	0.901	1.31	38	0.932
750	0.80	0.36	0.952	1.70	49	0.987

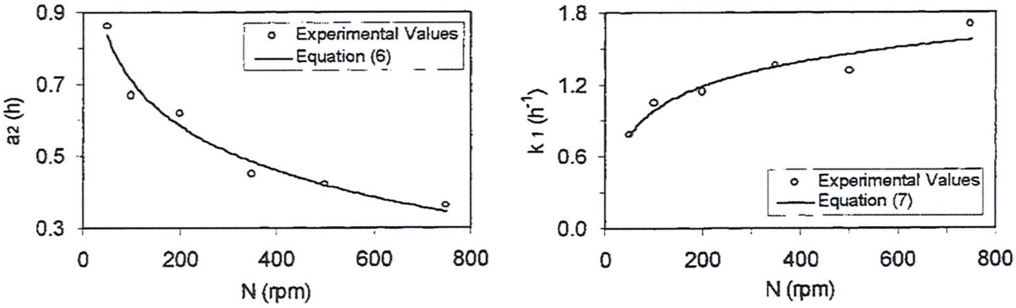


Figure 2 Variation of parameters a_2 and k_1 as a function of the agitation rate

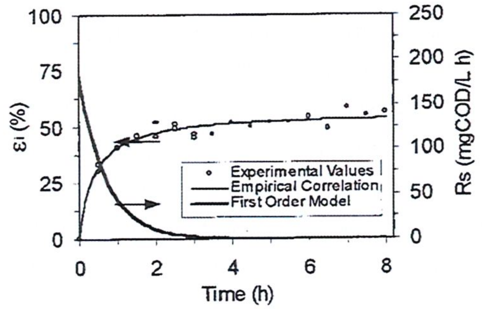
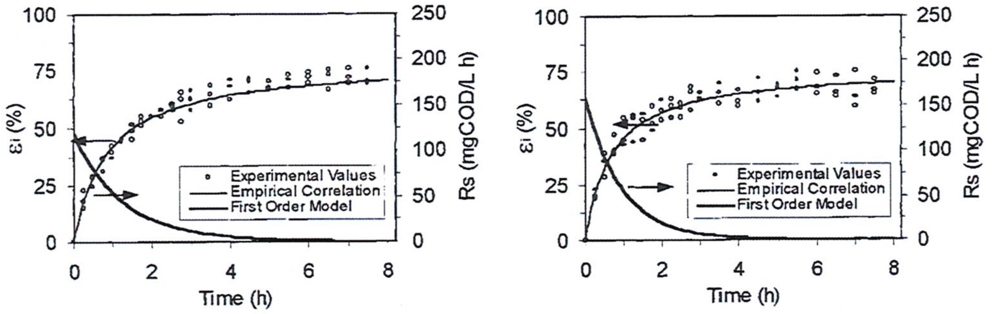


Figure 3 Profiles of the organic matter removal conversion determined experimentally and estimated by Equation (4) and of the organic matter removal conversion rates estimated by the first-order model (Equation 5) during the batch for the condition of no agitation



(a)

(b)

Figure 4 Profiles of the organic matter removal conversion determined experimentally and estimated by Equation (4) and of the organic matter removal conversion rates estimated by the first-order model (Equation 5) during the batch for the condition of 50 rpm (a) and 100 rpm (b)

the sequential batch time may be reduced and, consequently, the operation of the system, optimized. It must be emphasized that the values observed for solids adhered to the support throughout the experiments, presented standard deviations less than 10%, showing that the modifications in the reactor's performance were due to the different agitation rates implemented and not to the biomass growth.

Conclusions

The results obtained in the current work allow us to conclude that the system attained stability and high efficiency and presented a short start-up period and high solids retention for all the adopted experimental conditions investigated, validating the proposed reactor configuration.

The effect of agitation on the system's efficiency was quantified, enabling fitting of an empirical correlation to the removal profile of organic matter during the batch. Herein, the parameter representing maximum removal (a_1) remained constant and the parameter representing the time at which 50% of this maximum removal is achieved (a_2) was shown to be a

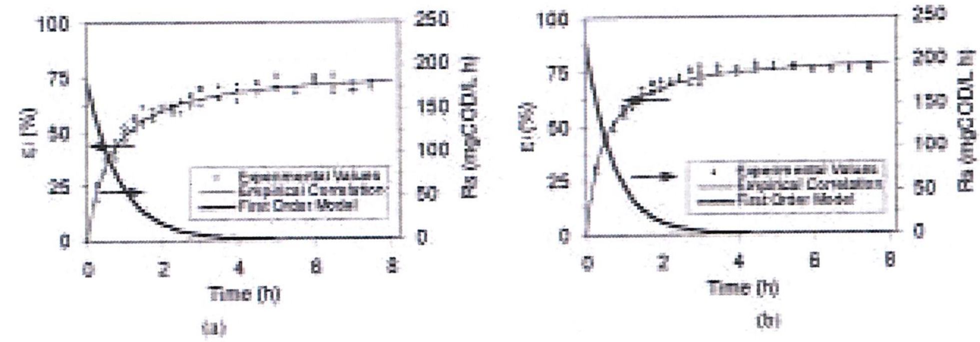


Figure 5 Profiles of the organic matter removal conversion determined experimentally and estimated by Equation (4) and of the organic matter removal conversion rates estimated by the first-order model (Equation 5) during the batch for the condition of 200 rpm (a) and 350 rpm (b)

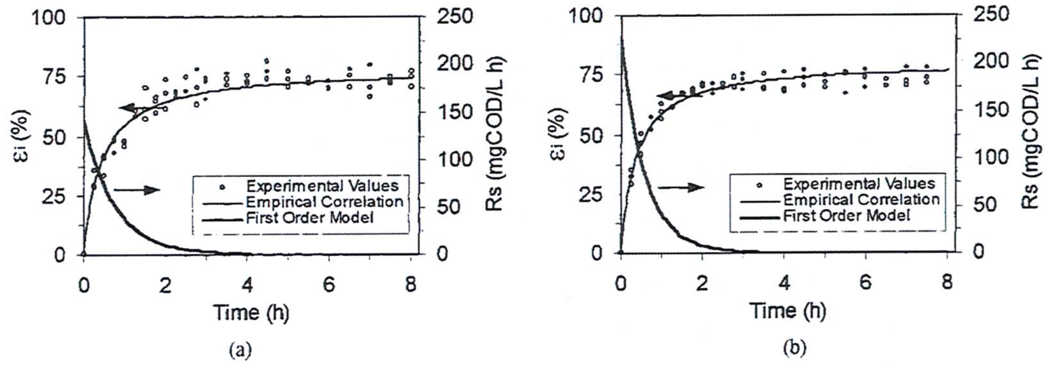


Figure 6 Profiles of the organic matter removal conversion determined experimentally and estimated by Equation (4) and of the organic matter removal conversion rates estimated by the first-order model (Equation 5) during the batch for the condition of 500 rpm (a) and 750 rpm (b)

logarithmic function of the agitation rate. These profiles allowed a reduction in cycle time from 8 to approximately 3 hours. A first-order kinetic model represented adequately the substrate degradation in the reactor. The apparent kinetic parameters (k_1), that represent the reaction and mass transfer phenomena, were fitted to an empirical model as a function of agitation rates, thus indicating that an increase in agitation leads to an improvement in mass transfer and, consequently, in increase in the kinetic parameter. The conclusions obtained by the fits of the two aforementioned models complement one another, indicating potential improvement in both the stability and performance caused by agitation in the anaerobic immobilized biomass system studied.

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Nomenclature

Symbols

a_1 – empirical kinetic parameter, dimensionless
a_2 – empirical kinetic parameter, h
BA – bicarbonate alkalinity concentration, $mgCaCO_3/L$
C_{ES} – filtered substrate concentration in the effluent, mgCOD/L
C_{ET} – non-filtered substrate concentration in the effluent, mgCOD/L
C_I – non-filtered substrate concentration in the influent, mgCOD/L
C_S – filtered substrate concentration in the reactor, mgCOD/L

C_{SO} – initial value of C_S, mgCOD/L
C_{SR} – residual filtered substrate concentration in the reactor, mgCOD/L
Cx – biomass concentration, gvs/L
k_1 – first-order kinetic parameter, h^{-1}
N – agitation rate, rpm
Rs – substrate uptake rate, mgCOD/L.h
SOR – specific organic removal, mgCOD/gvss
t – time, min or h
TS – total solids concentration, mg/L or mg/g-foam
TSS – total suspended solids concentration, mg/L or mg/g-foam
TVA – total volatile acids concentration, mgHAc/L
V – influent volume treated in each cycle, mL
VS – volatile solids concentration, mg/L or mg/g-foam
VSS – volatile suspended solids concentration, mg/L or mg/g-foam
ε_T – substrate removal efficiency considering non-filtered samples, %
ε_S – substrate removal efficiency considering filtered samples, %
ε_i – substrate removal efficiency in the reactor considering filtered samples, %
μs – specific substrate uptake rate, gCOD/gvss.h

Abbreviations

ASBR – anaerobic sequential batch reactor
COD – chemical oxygen demand
VSS – volatile suspended solids

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