

# TREATMENT OF LOW-STRENGTH WASTEWATER USING IMMOBILIZED BIOMASS IN A SEQUENCING BATCH EXTERNAL LOOP REACTOR: INFLUENCE OF THE MEDIUM SUPERFICIAL VELOCITY ON THE STABILITY AND PERFORMANCE

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**Abstract** - An anaerobic sequencing batch bioreactor with external circulation of the liquid phase wherein the biomass was immobilized on a polyurethane foam matrix was analyzed, focussing on the influence of the liquid superficial velocity on the reactor's stability and efficiency. Eight-hour cycles were carried out at 30°C treating glucose-based synthetic wastewater around 500 mgDQO/L. The performance of the reactor was assessed without circulation and with circulating liquid superficial velocity between 0.034 and 0.188 cm/s. The reactor attained operating stability and a high organic matter removal was achieved when liquid was circulated. A first order model was used to evaluate the influence of the liquid superficial velocity ( $v_s$ ), resulting in an increase in the apparent first order parameter when  $v_s$  increased from 0.034 to 0.094 cm/s. The parameter value remained unchangeable when 0.188 cm/s was applied, indicating that beyond this value no improvement on liquid mass transfer was observed. Moreover, the necessary time to reach the final removal efficiency decreased when liquid circulation was applied, indicating that a 3-hour cycle could be enough.

**Keywords:** anaerobic sequencing batch reactor; immobilized biomass; liquid external circulation; polyurethane foam.

## INTRODUCTION

Anaerobic sequencing batch reactors (ASBR) have been widely studied for wastewater treatment due to some advantages as good solids retention, elimination of the secondary sedimentation step, efficient operating control, relatively high organic matter removal efficiency and simple operation.

Moreover, it could be used to treat some wastewater discharged in an intermittent way (Zaiat *et al.*, 2001). Ndon & Dague (1997a, 1997b) and Brito *et al.* (1997) indicate that the anaerobic sequencing batch reactors are a good alternative of lower-cost treatment of low-strength industrial and municipal wastewater.

The ASBR operation is composed of four steps:

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feed, reaction, settling and liquid withdrawal (Dague *et al.*, 1992). During the reaction step some kind of mixture should guarantee an effective contact between the biomass and the bulk liquid in order to improve the overall organic matter uptake rates. The necessary mixing can be provided by circulation of the biogas produced (Sung & Dague, 1995). However, for low strength wastewater the biogas production is insufficient and an alternative mixing may be necessary (Brito *et al.*, 1997). Circulation of the bulk liquid through a pump (Hirl & Irvine, 1996; Brito *et al.*, 1997) or mechanical agitation (Ratusznei *et al.*, 2000) can also be used.

The biomass settling, necessary to assure sedimentation of the biomass providing the solids removal efficiency, may be the determining step of the cycle time since it is directly related to the formation of self-immobilized biomass as granules with good settleability. However, present knowledge of the self-immobilization process is not sufficient to guarantee its occurrence and control (Zaiat *et al.*, 1997a). Hence, immobilization of biomass in inert supports is useful to provide biomass retention even under adverse operating conditions. Ratusznei *et al.* (2000) used anaerobic biomass immobilized in polyurethane foam to treat domestic synthetic wastewater in a stirred ASBR, achieving high organic matter removal efficiency and high solids retention, eliminating the settling step.

However, utilization of immobilized biomass on inert support introduces internal and external mass transfer resistances from the liquid bulk phase to the anaerobic biomass aggregates that can reduce the organic matter uptake rates, worsening the performance of the reactor. In this way implementation of mixing in the reactor becomes very important since the overall mass transfer rates can be increased and the ASBR operation improved.

This work investigates an anaerobic sequencing batch reactor configuration with an external liquid circulation system and immobilized biomass on an inert support, treating a low strength glucose-based synthetic wastewater. The influence of the superficial velocity on the reactor's performance was evaluated through utilization of different circulating flow rates.

## MATERIAL AND METHODS

The anaerobic bioreactor with external circulation of the liquid phase is shown in Figure 1. The reactor consists of a cylindrical flask with an external diameter of 60 mm, 460 mm of height and 3.5 mm of

wall thickness, resulting approximately in a work volume of 1.0 L. The fixed-bed with 410 mm of height, composed of 5-mm cubic polyurethane foam matrices (apparent density of 23 kg/m<sup>3</sup>) containing the immobilized biomass and confined between two punctured stainless steel disks, resulting in a bed porosity of 40% (Zaiat *et al.*, 1997b). The reactor was inoculated with granular anaerobic sludge with 54 mg-tvs/g-sludge taken from an UASB reactor treating poultry slaughterhouse wastewater. The sludge was immobilized on 20 g of foam as described by Zaiat *et al.* (1994), attaining solid concentrations of 0.66 g-ts/g-foam and 0.53 g-tvs/g-foam, thus resulting in an initial volatile solids content (X) of 10.6 g in the reactor volume.

The liquid phase circulating system was composed of an adjustable peristaltic flow pump and a reservoir with 40 mm of external diameter, 200 mm of height, 3.3 mm of wall thickness, with a volume about 0.2 L. Thus, the total reactor volume was 1.2 L.

Batch cycles of eight hours were carried out at a temperature of 30 ± 1°C, treating approximately 500 mL of a glucose-based synthetic wastewater with approximately 500 mg COD/L, prepared with glucose (500 mg/L), urea (125 mg/L), NiSO<sub>4</sub>·6H<sub>2</sub>O (1 mg/L), FeSO<sub>4</sub>·7H<sub>2</sub>O (5 mg/L), FeCl<sub>3</sub>·6H<sub>2</sub>O (0.5 mg/L), CaCl<sub>2</sub>·H<sub>2</sub>O (47 mg/L), CoCl<sub>2</sub>·6H<sub>2</sub>O (0.08 mg/L), Na<sub>2</sub>SeO<sub>3</sub> (0.07 mg/L), KH<sub>2</sub>PO<sub>4</sub> (85 mg/L), K<sub>2</sub>HPO<sub>4</sub> (22 mg/L), Na<sub>2</sub>HPO<sub>4</sub> (33 mg/L) and NaHCO<sub>3</sub> (500 mg/L).

The reactor operation without and with liquid circulation was composed of three steps: feed (5 min), reaction (470 min) and liquid withdrawal (5 min), since the settling step was eliminated due to the presence of immobilized biomass. Both feed and liquid withdraw steps were performed by an adjustable peristaltic flow pump. Moreover, during these two steps the circulation pump was turned off. The liquid flow rates used were 1.1, 3.0 and 6 L/h, resulting in liquid superficial velocities of 0.034, 0.054 and 0.188 cm/s, respectively. These values were based on the results obtained by Zaiat *et al.* (1997a,b) studying the influence of superficial velocities on the solids retention in the same inert support. The early velocities were calculated by Equation (1), where Q is the liquid circulation flow rate, A is the internal cross-sectional area of the reactor and φ is the fixed-bed porosity. Each test took at least 20 days (60 cycles).

$$v_s = \frac{Q}{\phi A} \quad (1)$$

The chemical oxygen demand (COD), total volatile acid (TVA), bicarbonate alkalinity (BA), total solids (TS), total volatile solids (TVS), total suspended solids (TSS), volatile suspended solids (VSS) 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 biogas composition was evaluated through gas chromatography. The discharged volume in each batch test was also monitored.

The reactor's performance was evaluated by the overall substrate removal efficiencies based on non-filtered and filtered samples. These parameters were calculated by Equations (2) and (3), respectively, where  $C_I$  is the influent non-filtered substrate concentration,  $C_{ET}$  is the effluent non-filtered substrate concentration,  $C_{ES}$  is the effluent filtered substrate concentration.

$$\varepsilon_T = \frac{C_I - C_{ET}}{C_I} \quad (2)$$

$$\varepsilon_S = \frac{C_I - C_{ES}}{C_I} \quad (3)$$

The organic volumetric loading (OVL), the specific organic loading (SOL) and the specific organic removal (SOR) were calculated by Equations (4), (5) and (6), respectively, where  $V_{dfed}$  was the daily treated influent volume,  $V_{fed}$  was the influent volume treated per cycle and  $V_{reactor}$  was the total volume of the reactor. Moreover, the anaerobic biomass amount ( $X$ ) was admitted as constant during the assays.

$$OVL = \frac{V_{dfed} C_I}{V_{reactor}} \quad (4)$$

$$SOL = \frac{OVL V_{reactor}}{X} \quad (5)$$

$$SOR = \frac{V_{fed} (C_I - C_{ES})}{X} \quad (6)$$

In order to examine the influence of superficial velocity on the reactor's performance, the filtered substrate concentration in the reactor profiles along the cycle ( $C_S$ ), calculated by Equation (7), was measured when the reactor was operated on a stable condition, i.e., when the filtered substrate, bicarbonate alkalinity and

total volatile acids effluent concentrations presented no significant variation from one cycle to another. In Equation (7),  $C_S$  is the filtered substrate concentration in the reactor and  $C_{S0}$  the initial value of  $C_S$ .

$$\varepsilon_i = \frac{C_{S0} - C_S}{C_{S0}} \quad (7)$$

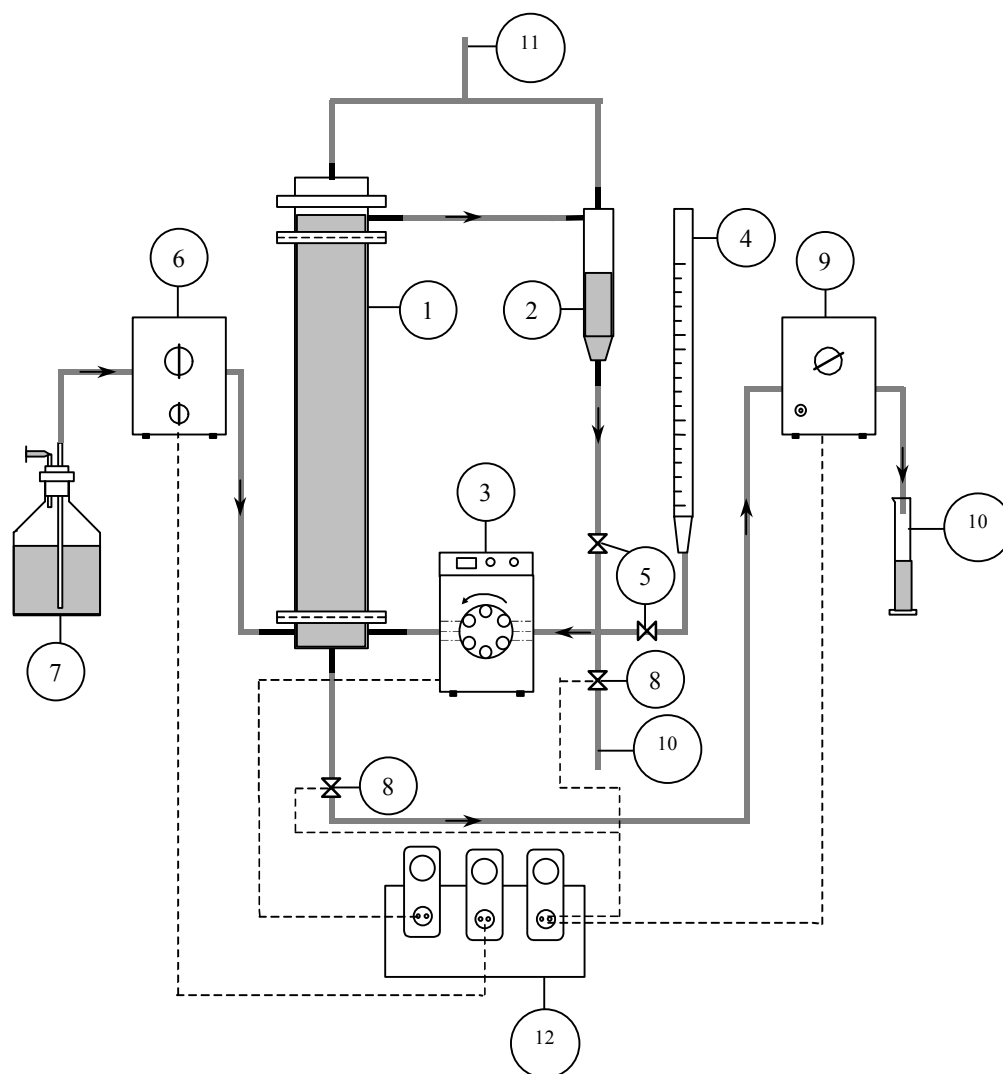
To obtain the filtered substrate concentration-time profile in the reactor for the condition without liquid circulation, the medium was homogenized just before the sample withdrawal in order to assure the measurement of the actual average concentration of the substrate in the reactor. For this reason, the following procedure was adopted. In a given cycle, at a certain time  $t_1$ , the medium was discharged, homogenized and then the sample was taken, leading to the first point of the profile. After completion of the above cycle, three consecutive undisturbed cycles were run with the purpose to eliminate the disturbance produced by the cited discharge. Then, during the next cycle, at time  $t_2 > t_1$ , the second sample was taken as described above leading to the second point of the profile. The above operation was repeated in order to obtain the entire profile. When the assays were carried out with liquid circulation, the filtered substrate concentration in the reactor profile was obtained in a single cycle, in which the samples were taken from the reservoir using a syringe.

Mathematical analysis of the influence of the superficial velocity on the reactor's dynamic efficiency was performed by non-linear fitting of the first order kinetic model to the transient profiles of filtered substrate concentration in the reactor ( $C_S$ ) during the cycle, shown in Equation (9) obtained from the material balance shown in Equation (8) and the initial condition (Equation 8-a), using the Levenberg-Marquardt numerical method. The parameter  $k_1^{app}$  stands for the apparent kinetic coefficient, as it embodies the intrinsic kinetic constant as well as the internal and external mass transfer resistances while the residual concentration ( $C_{SR}$ ) represents the value of filtered substrate concentration in the reactor when the value of the reaction rate ( $R_s$ ) was zero.

$$-\frac{dC_S}{dt} = \mu_S C_X = R_S = k_1^{app} (C_S - C_{SR}) \quad (8)$$

$$t = 0 \Rightarrow C_S = C_{S0} \quad (8-a)$$

$$C_S = C_{SR} + (C_{S0} - C_{SR}) \exp(-k_1 t) \quad (9)$$



**Figure 1:** Scheme of the anaerobic sequencing batch reactor with external circulation of the liquid phase and immobilized biomass: 1) reactor containing immobilized biomass; 2) external reservoir; 3) circulation pump; 4) flow rate meter; 5) valves; 6) feed pump; 7) synthetic wastewater reservoir; 8) discharge valve; 9) discharge pump; 10) effluent outlet; 11) biogas outlet; 12) control unit; — hydraulic connections; ---- electric connections.

## RESULTS AND DISCUSSION

The mean values and the respective standard errors of the main monitored variables in the reactor in both influent and effluent are shown in Tables 1, 2 and 3. The low standard deviations observed in effluent samples (Table 1) indicate that reactor operation was sufficiently stable. The pH values, the low values of total volatile acids concentration, the

generation of bicarbonate alkalinity in the effluent and the biogas composition confirm a stable methanogenic process in the reactor (Table 2). The influent and effluent values of solids (Table 3) indicate that washout was not effective during the experimental period since the polyurethane foam matrices provided suitable condition for biomass retention even when the highest superficial velocity was applied.

The value of  $V_{fed}$  shown in Table 1 was lower for the no circulation condition due to the extra volume needed to perform circulation, i.e., the volume needed for circulation of the flow pump. In Table 2, the methane content in the first experiment is higher probably due to the higher loss of biogas when circulation was implemented. Moreover, the values obtained for TSS and VSS are very low, perhaps meaningless, however, these values are important to show the quality of the effluent in a process without settling step.

A relatively high efficiency was achieved for all studied conditions (Table 1). The results indicated the improvement from 83% to 95% for the non-filtered substrate COD removal efficiency ( $e_T$ ), when circulation was implemented. However no significant enhancement in the efficiency was observed as the liquid superficial velocity was increased due to the extended cycle time (8 hours).

The organic volumetric loading in the reactor was 498 mg COD/L.d, the specific organic loading was 56.4 mg COD/g-tvs.d and the specific organic removals were 15.7 mg COD/g-tvs.L and 17.7 mgCOD/g-tvs.L, respectively, for the conditions without and with circulation. The values of total reactor volume, average treated volume per cycle, biomass content in the reactor, average non-filtered influent substrate concentration and average non-filtered effluent substrate concentration without and with circulation were 1.2 L, 380 mL, 10.6 g-tvs, 525 mg COD/L, 87 mgCOD/L and 32 mgCOD/L, respectively. These are low values but typical for low-strength wastewater.

In order to verify how the organic matter removal took place, the filtered substrate profiles along a cycle time were taken for all studied conditions, evaluating the influence of superficial velocity on the dynamic efficiency of the reactor, when non-filtered

and filtered effluent substrate concentration presented no significant variation from one cycle to another. Figures 2 to 5 show the experimental and fitted values of the conversion and organic material removal rate profiles during a batch cycle for all studied conditions.

The results shown in Table 4 are divided in two groups: (a) without circulation, of which the mass transfer is based on diffusion phenomenon (the value of  $C_{SR}$  is higher than the others) and (b) with circulation, of which the mass transfer is based on convection phenomenon. Therefore, the dependence of the apparent kinetic parameter on the superficial velocity should be taken into account only for the conditions for which circulation was implemented.

The influence of the liquid superficial velocity on the behavior of the dynamic substrate concentration profile can be assessed through the variation of apparent kinetic coefficient ( $k_1^{app}$ ) values (Table 4), which is directly related to the liquid-phase mass transfer coefficient. An increase in the apparent first order parameter was observed when the liquid superficial velocity increased from 0.034 to 0.094 cm/s, remained unchangeable when the superficial velocity was increased to 0.188 cm/s. This indicates an effective influence of the liquid-phase mass transfer on the overall reaction rate and, consequently, on the overall performance of the process, indicating that the improvement due to the convection effects attain a limit level. Furthermore, these results suggest that the increase in the liquid superficial velocity decreased the time required to reach the final removal efficiency since the organic matter removal rate only presented significant values for the first three hours of the operation cycle. These results suggest that the cycle time can be reduced as the liquid superficial velocity is increased, thus permitting optimization of the performance of the reactor.

**Table 1: Mean values of substrate concentrations, efficiency and effluent volume monitored in the reactor operated at different superficial velocities.**

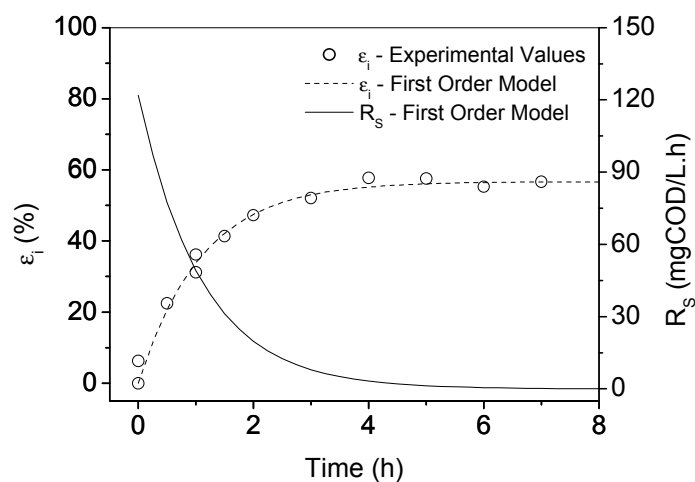
$v_s$ ( $10^{-2}$ cm/s)	Q (L/h)	$C_1$ (mgCOD/L)	$C_E$ (mgCOD/L)		e (%)		$V_{fed}$ (mL)
			$C_{ET}$	$C_{ES}$	$e_T$	$e_S$	
0	0	522 ± 9	87 ± 18	75 ± 16	83 ± 3	86 ± 3	271 ± 23
3.4 ± 0.2	1.1 ± 0.1	518 ± 21	25 ± 2	22 ± 2	95 ± 1	96 ± 1	346 ± 8
9.4 ± 0.2	3.0 ± 0.1	521 ± 8	35 ± 24	23 ± 14	95 ± 5	96 ± 3	441 ± 24
18.8 ± 0.6	6.0 ± 0.2	537 ± 8	36 ± 3	25 ± 5	93 ± 1	95 ± 1	462 ± 9

**Table 2: Mean values of bicarbonate alkalinity, total volatile acids and pH monitored in the reactor operated at different superficial velocities.**

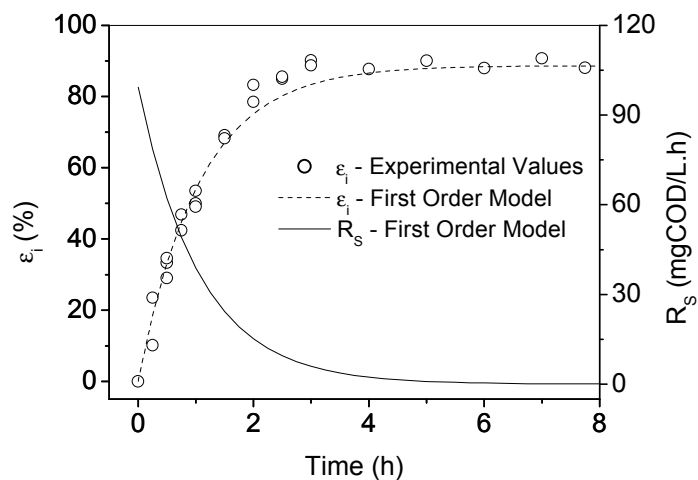
$v_s$ ( $10^{-2}$ cm/s)	BA (mgCaCO <sub>3</sub> /L)		TVA (mgHAc/L)		pH		Biogas Composition (%)	
	Influent	Effluent	Influent	Effluent	Influent	Effluent	CH <sub>4</sub>	CO <sub>2</sub>
0	283 ± 10	372 ± 34	46 ± 8	74 ± 21	7.4 ± 0.1	6.7 ± 0.2	63 ± 12	37 ± 12
3.4 ± 0.2	285 ± 14	375 ± 18	47 ± 8	45 ± 14	7.7 ± 0.1	7.3 ± 0.1	52 ± 4	48 ± 4
9.4 ± 0.2	295 ± 8	390 ± 10	47 ± 4	53 ± 6	7.7 ± 0.1	7.1 ± 0.1	51 ± 4	49 ± 4
18.8 ± 0.6	292 ± 24	370 ± 13	51 ± 5	62 ± 10	7.6 ± 0.1	7.0 ± 0.1	52 ± 3	48 ± 3

**Table 3: Mean values of total and suspended solids concentration monitored in the reactor operated at different superficial velocities.**

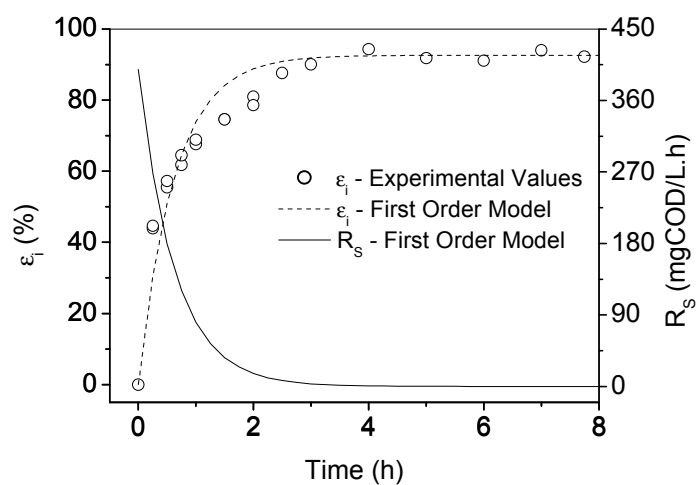
$v_s$ ( $10^{-2}$ cm/s)	TS (mg/L)		TVS (mg/L)		TSS (mg/L)		VSS (mg/L)	
	Influent	Effluent	Influent	Effluent	Influent	Effluent	Influent	Effluent
0	1092 ± 83	731 ± 90	727 ± 97	353 ± 81	30 ± 13	31 ± 9	15 ± 7	18 ± 7
3.4 ± 0.2	1096 ± 29	687 ± 37	707 ± 42	284 ± 23	33 ± 15	30 ± 18	8 ± 5	14 ± 6
9.4 ± 0.2	1011 ± 119	728 ± 28	636 ± 82	339 ± 34	51 ± 2	41 ± 21	22 ± 13	18 ± 18
18.8 ± 0.6	1036 ± 63	713 ± 115	692 ± 85	438 ± 47	41 ± 14	48 ± 21	20 ± 15	24 ± 17



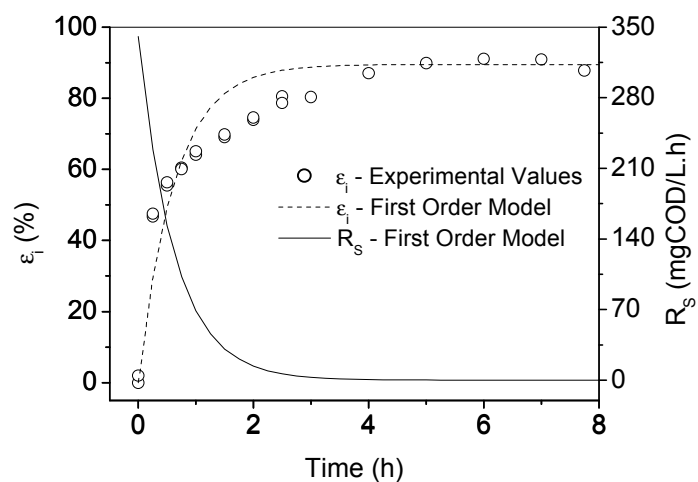
**Figure 2: Experimental and fitted values of the conversion and organic material removal rate profiles during a batch cycle for the condition without liquid circulation.**



**Figure 3:** Experimental and fitted values of the conversion and organic material removal rate profiles during a batch cycle for the condition with superficial velocity of 0.034 cm/s.



**Figure 4:** Experimental and fitted values of the conversion and organic material removal rate profiles during a batch cycle for the condition with superficial velocity of 0.094 cm/s.



**Figure 5:** Experimental and fitted values of the conversion and organic material removal rate profiles during a batch cycle for the condition with superficial velocity of 0.188 cm/s.

**Table 4: Values of apparent kinetic parameter, residual substrate concentration and determination coefficient ( $r^2$ ).**

$v_s$ ( $10^{-2}$ cm/s)	$k_1^{app}$ ( $h^{-1}$ )	$C_{SR}$ (mg/L)	$r^2$
0	$0.91 \pm 0.06$	$102 \pm 3$	0.979
$3.4 \pm 0.2$	$0.94 \pm 0.04$	$13 \pm 1$	0.980
$9.4 \pm 0.2$	$1.6 \pm 0.1$	$20 \pm 4$	0.950
$18.8 \pm 0.6$	$1.6 \pm 0.1$	$25 \pm 4$	0.903

## CONCLUSIONS

The results obtained in this work permitted to conclude about the enhancement performance in an anaerobic sequencing batch reactor with immobilized biomass due to implementation of the external liquid circulation, which improves the liquid mass transfer from the liquid bulk phase to immobilized biomass. Furthermore, the inert support of polyurethane foam was very adequate, since it guaranteed suitable solid retention even at high liquid superficial velocity, thus permitting the suppression of the settle step in ASBR operation.

The organic matter removal efficiency increased from 83% to 95% for the non-filtered substrate COD removal efficiency when the liquid circulation was implemented as a consequence of the better contact between biomass and substrate, thus improving the overall organic matter uptake rate.

The kinetic study revealed that the value of the first-order apparent kinetic coefficient was approximately duplicated when the liquid superficial velocity was increased from 0.034 to 0.094 cm/s. Such a parameter remained unchangeable for the highest value of 0.188 cm/s. This result shows the possibility of minimizing of the time required to obtain the final removal efficiency through implementation of external liquid circulation.

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## NOMENCLATURE

### Symbols

A	reactor cross-sectional area, $cm^2$
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, $mgCOD/L$
$C_{S_0}$	initial value of $C_S$ , $mgCOD/L$
$C_{SR}$	residual filtered substrate concentration in the reactor, $mgCOD/L$
$C_X$	biomass concentration, $g-tvs/L$
$k_1^{app}$	apparent first order kinetic parameter, $h^{-1}$
OVL	organic volumetric loading, $mgCOD/L.d$
Q	external liquid flow rate, $L/h$
$R_S$	filtered substrate uptake rate, $mgCOD/L.h$
SOL	specific organic loading, $mgCOD/g-tvs.d$
SOR	specific organic removal, $mgCOD/g-tvs$
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 acid concentration, $mgHAc/L$
TVS	total volatile solids concentration, $mg/L$ or $mg/g-foam$
$V_{dfed}$	daily treated influent volume, L
$V_{fed}$	influent volume treated per cycle, $mL$ or L
$V_{reactor}$	total volume of the reactor per cycle, L
$v_s$	liquid superficial velocity, $cm/s$
VS	volatile solids concentration, $mg/L$ or $mg/g-foam$
VSS	volatile suspended solids concentration, $mg/L$ or $mg/g-foam$
X	biomass amount, $g-tvs$



**Greek Letters**

$\phi$	fixed-bed porosity, %
$\epsilon_i$	substrate removal efficiency in the reactor considering filtered substrate concentration, %
$\epsilon_s$	substrate removal efficiency considering filtered substrate concentration, %
$\epsilon_T$	substrate removal efficiency considering non-filtered substrate concentration, %
$\mu_s$	specific substrate uptake rate, mgCOD/g-tvs.h

**Abbreviations**

ASBR	anaerobic sequential batch reactor
COD	chemical oxygen demand
ts	total solids
tvs	total volatile solids

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